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Phytoplankton Dynamics in the Very Low Salinity Region of the James River Estuary, Virginia, U.S.A.

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PHYTOPLANKTON DYNAMICS IN THE VERY LOW SALINITY REGION OF THE JAMES RIVER ESTUARY, VIRGINIA, U.S.A.

by

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ABSTRACT

PHYTOPLANKTON DYNAMICS IN THE VERY LOW SALINITY REGION
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Surface phytoplankton biomass was measured at approximately one month intervals from July 1986 to August 1987 along the axis of the main channel in the James River estuary, Virginia. During summer and autumn when river discharge was less than 120 m^3sec^{-1}, there was a peak phytoplankton biomass in the very low salinity region (defined as the location where surface salinity measured less than 0.5 o/oo) and this peak represented five to ten times greater biomass than adjacent waters further up and downstream. The peak biomass occurred independent of the tidal state and the location of nutrient inputs. The peak biomass disappeared during winter and spring, and nutrient limitation was not responsible for the low phytoplankton biomass, indicating that physical, not chemical, factors were controlling the abundance within this zone.

The peak biomass was hypothesized to be caused by hydrodynamic trapping, the same mechanism involved in the formation of the turbidity maximum, and by increased phytoplankton residence time during periods of low river discharge. Close balance of sinking rates of dominant phytoplankton species with the net upward vertical water velocity, relatively large netplankton biomass (retained by 28 um screen),

exhaustion of dissolved silicate, relatively high ratio of particulate biogenic silica to particulate organic carbon, and relatively low ratio of particulate organic carbon to chlorophyll a in the very low salinity region indicate that diatoms are selectively trapped within this zone.

As river discharge increased during winter and spring, the magnitude of the turbidity maximum increased but the peak biomass disappeared as a result of decreased residence time of phytoplankton, decreased sinking rate of phytoplankton due to increased water viscosity at low temperature, and increased net-circulation which requires larger sinking rates to develope the peak biomass in the turbidity maximum zone.

There were some differences between the turbidity maximum zone and the location of the peak biomass. High biomass in the very low salinity region decreased very rapidly before the 1.5 o/oo isohaline, while the turbidity maximum zone encompassed a much broader area. Relatively high ratios of chlorophyll a to phaeopigments, and low ratios of particulate organic carbon to nitrogen in the very low salinity region suggest that phytoplankton within this zone grew under good physiological conditions. Mass mortality due to osmotic stress placed on freshwater phytoplankton appears to be the best explanation for the rapid loss of biomass.

The occurrence of the peak biomass and selective trapping of diatoms in the very low salinity region are important to food-webs and also to geochemical processes in the estuary.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

GENERAL INTRODUCTION

1-1 Introduction

The upward extension of an estuary, just upstream of the limit of salt intrusion, is an important site for chemical and biological processes. Many physical environmental factors are involved in complex interactions. A knowledge of the chemical reactions which occur within this zone is essential for the precise estimation of the mass balance of elements and for the prediction of the fate of waste products discharged into rivers and the coastal region (Morris et al., 1982). Phytoplankton study within this zone is important for understanding the biogeochemical processes which occur in the estuary and for investigating the fate of freshwater phytoplankton. The variations of phytoplankton biomass within this zone may regulate some geochemical processes and phytoplankton dynamics in the seaward portion of an estuary. From the standpoint of managing water quality, the area has a eutrophication problem because maximum phytoplankton biomass occurs during periods of low river discharge (Filardo and Dunstan, 1985) and the area is easily exposed to anthropogenic nutrient sources (Lipson, 1973; Bennett et al., 1986). Phytoplankton within this zone has received little attention to date, perhaps because this geographic area falls between the traditional realm of marine and freshwater ecologist.

Morris et al. (1978) observed the rapid decrease of dissolved oxygen within the 0.10 - 1.00 o/oo mixing segment of the Tamar estuary, England.

Oxygen supersaturation at the extreme seaward and freshwater ends of the estuary was attributed to active primary production of freshwater phytoplankton and the sharp oxygen depletion within the 0.10 - 1.00 o/oo mixing segment was hypothesized to be a result of mass mortality of freshwater phytoplankton incapable of withstanding the sudden osmotic and compositional change of the mixing segment. It was reported that the mass mortality resulted in a continuous plasmolytic release of easily degradable dissolved organic material. High concentration of phytoplankton biomass in the very low salinity region and rapid decrease of the biomass before the approximately 2 o/oo isohaline in the James River estuary were also attributed to the osmotic stress encountered by the freshwater phytoplankton upon advection into the estuary (Filardo and Dunstan, 1985). They further showed the inverse relationship of phytoplankton biomass in the very low salinity region with river discharge, suggesting the hydrodynamic control over the biomass.

High phytoplankton biomass in the very low salinity region and rapid decrease of the biomass was also reported in the Delaware estuary by Sharp et al. (1982) and Pennock (1983). However, the initial decrease in phytoplankton biomass was attributed to an increase in suspended sediment in the low salinity region which restricts the amount of photosynthesis by limiting the photic zone. Edzwald et al. (1974) and Avnimelech (1982) attributed the initial decrease in phytoplankton biomass to mutual flocculation of algae and colloidal particles when freshwater mixes with seawater. The increase in flocculation results in an increased sedimentation of phytoplankton together with sediments.

Consequently, the hypotheses suggested for the initial decrease in phytoplankton biomass in low salinity regions are osmotic stress of

freshwater phytoplankton upon advection into the estuary, increased settling velocity as a result of flocculation of algae and clays, and decreased light penetration due to high concentration of suspended sediment in the low salinity area. Studies of initial decrease in phytoplankton biomass imply that phytoplankton biomass in the freshwater zone is generally higher than that in mid-estuary, but the biomass in the freshwater zone, beyond the limit of salt intrusion, was not investigated.

A different situation was described by Cloern et al. (1983) and Anderson (1986) who reported a peak phytoplankton biomass in the upper reach of the northern San Francisco Bay estuary and the Chesapeake Bay tributaries during periods of low river discharge. They showed that the peak region has several times greater biomass than adjacent waters further up and downstream. The peak biomass in the San Francisco Bay estuary occurred at the 3 - 4 o/oo mixing segment, while the peak biomass in the Chesapeake Bay tributaries occurred in the fresh/seawater interface, just upstream of salt intrusion.

Cloern et al. (1983) and Anderson (1986) suggested that formation of the peak biomass is a consequence of the same physical mechanisms that create local maxima of suspended sediments in partially-mixed estuaries: density - selective retention of particles by estuarine circulation. It was suggested that diatoms are selectively trapped in the turbidity maximum zone because their relatively high sinking rates are approximately the same as the vertical currents in the "null" zone. Netplankton biomass, dissolved silicate distribution and dominant phytoplankton species in the null zone were presented as the evidences for the trapping mechanisms. However, relative importance of diatoms in

particulate organic carbon and physiological state of the diatoms in the peak biomass zone were not reported. Moreover, the trapping mechanism suggested for the peak phytoplankton biomass implies that stronger magnitude of the turbidity maximum is related to higher concentration of phytoplankton biomass in the very low salinity region. However, the distribution and abundance of phytoplankton in an estuary are determined by the biological processes in addition to the transport mechanism that affects suspended sediments. Agal cells also grow, divide, decompose or are consumed unlike the inorganic particles. Relationship between the magnitude of the turbidity and phytoplankton biomass within the very low salinity region has not been studied.

In addition to the hypothesized trapping mechanism as a fact in producing the peak biomass, transport of phytoplankton from shoals to adjacent main channels is suggested in the northern San Francisco Bay estuary (Cloern et al., 1983). The northern San Francisco Bay estuary has a shallow and expansive embayment compared to the James River estuary where the shoals are very narrow. The peak biomass in the northern San Francisco Bay estuary comprises more than 80% of neritic diatoms, which are transported from the productive shallow shoals to the main channel and are trapped in the turbidity maximum zone (Cloern et al., 1983). However, in the James River estuary, the major source contributing to the peak biomass is probably freshwater production. Freshwater species of diatoms are reported as the major component of the very low salinity region (Filardo and Dunstan, 1985; Anderson, 1986). The importance of shoals in causing the peak biomass in the James River estuary has not been studied.

Though both Cloern et al. (1983) and Anderson (1986) emphasized the

importance of river discharge in causing the peak biomass, they did not report effect of river flow on the magnitude of the peak biomass quantitatively. Moreover, the disappearance of the peak biomass in the James River estuary was not shown because of the lack of winter data.

In addition to the hypothesized trapping mechanism, Anderson (1986) suggests that the rapid remineralization of nutrients early in the transition from a fresh to saline environment supports the high biomass in the Chesapeake Bay tributaries. Dissolved silicate distribution in the Rappahannock River estuary showed an increase in concentration at mid-estuary, after near complete removal of the riverine supply by the diatoms at the fresh/seawater interface during periods of low river discharge. However, Anderson (1986) did not report the behavior of other nutrients such as nitrate and phosphate which are essential for phytoplankton growth. Moreover, any concentration of nutrient was not determined except dissolved silicate during late spring and summer in the James River estuary. The location of nutrient inputs as well as the rapid regeneration may be involved in causing the peak biomass. Lippson (1973) attributed the high chlorophyll concentration in the upper Potomac and Patuxent rivers to the enrichment from Washington D.C. It has not been studied whether the location of nutrient inputs is important in causing the peak biomass in the James River estuary.

Hass (1977) observed the oscillation of the James, York and Rappahannock Rivers between vertical homogeneity and stratification in conjunction with the monthly spring - neap tide. Webb and D'Elia (1980) studied the effects of the spring tidal destratification on nutrient and oxygen distribution in the York River. During the periods of neap tide, vetical profiles of nutrient and oxygen strongly reflected the

stratification state of the estuary, while during the periods of spring tide the vertical profiles showed destratification. It was suggested that vertical mixing accompanying destratification replenishes oxygen in the deep water, allowing aerobic processes to proceed, which may accelerate the input of benthic regenerated nutrients into the euphotic zone. In addition to the lunar cycle of tide, diurnal cycles of tide, flooding and ebbing tide, affect the vertical distribution of total suspended matter with varying current speed (Nichols, 1972). It has not been investigated whether the peak biomass occurs independent of the tidal state, and how much the location and the magnitude of the peak biomass change according to the tidal state.

1-2 Objectives

The objectives of the study were:

(1) to observe the occurrence, the position and the magnitude of peak phytoplankton biomass in the very low salinity region of the James River estuary (the peak biomass was positioned by the distance from a fixed position of Newport News Shipyard and by the surface salinity measured at the peak, and the magnitude of the peak biomass was defined as the maximum concentration of chlorophyll a in the peak zone);

(2) to study some factors which may affect the occurrence, the position, and the magnitude of the peak phytoplankton biomass (tidal state, amount of river discharge, and nutrients were assumed as possible factors);

(3) to investigate the processes involved in causing the observed peak phytoplankton biomass (it was hypothesized that peak biomass is caused by hydrodynamic trapping, the same mechanism involved in the formation of the turbidity maximum in a partially-mixed estuary).

1-3 Literature Review

Salinity Effects on Growth and Photosynthesis of Phytoplankton

Salinity is considered an important ecological variable in the marine environment, particularly in estuarine regions and inshore areas where planktonic algae are often subjected to widely fluctuating salt concentrations. Algae face problems of regulating movement of water between the cell itself and its environment. When a cell is subjected to a dilution stress, the water will enter the cell causing the cell to swell, while in a salt stress, water exits from the cell leading to plasmolysis (Guillard, 1962).

It has been demonstrated that the internal osmotic pressure of planktonic algae is regulated through the synthesis or breakdown of organic molecules. The osmotically active solutes (osmolytes) within cells are quite different from those outside, and the major osmolytes are restricted to a few classes of low molecular weight metabolic products such as polyhydric alcohols and free amino acids: glycerol for green flagellates, Dunaliella (Craigie and McLachlan, 1964; Ben-Amotz, 1975; Jones and Galloway, 1979; Brown and Borowitzka, 1979) and Asteromonas (Ben-Amotz and Avron, 1980), cyclitol cyclohexanetetrol for a marine haptophyte, Monochrysis lutheri (Craigie, 1969), mannitol for Platymonas suecica, a green flagellate (Hellebust, 1976), isofloridoside for a freshwater chrysophyte, Ochromonas malhamensis (Kaus, 1967), sucrose for a freshwater algae, Scenedesmun obliquus (Wetherell, 1963), mannose for an estuarine pennate diatom, Cylindrotheca fusiformis (Paul, 1979),

proline for a marine centric diatom, Cyclotella cryptica (Liu and Hellebust, 1976) and a marine unicellular alga, Nannochloris bacillaris (Brown and Hellebust, 1980).

Among the commonly utilized organic osmolytes, none has a positive charge that could form a complex with generally negatively charged cell metabolites (Yancey et al., 1982). It was proposed that the selective advantages of the organic osmolyte system are, first, no special restrictions on the macromolecular structure of the organisms that use them, and, second, greatly reduced need for modifying proteins to function in concentrated intracellular solutions.

When osmoregulation is defined as the processes and mechanisms by which plants adjust the osmotic pressure in their cells, the osmoregulation must satisfy both the growth requirement for sufficient turgor pressure and the physiological demand that the osmolytes do not interfere with the efficient operations of metabolic reactions.

Many studies demonstrate that there is a wide range of salinities tolerated by euryhaline organisms. McLachlan (1961) grew nine species of unicellular marine algae at various salinities from 2.5 to 35 o/oo. A distinct salinity optimum was not found in Monochrysis, Syracosphaera, Cyclotella, Thalassiosira and Cryptomonas, showing slight reduction in growth rates with increasing salinity. Olithodiscus showed maximum growth at salinity 15 o/oo and Amphidinium at 25 o/oo. The salinity range at which O. leteus occurs in natural water was reported from 3 to 33 o/oo (Tomas, 1978). The species showed an increased tolerance to low salinity with increasing temperature. Liu and Hellebust (1976) demonstrated that C. cryptica can grow well over a salinity range from 10 to 150% artificial sea water, although the species showed progressive

reduction in growth rates with increasing salinity. Asteromonas gracilis, present in salt marshes and small brine ponds which are often subjected to widely fluctuating salt concentration (Floyd, 1978), can tolerate a broad range of salt from 0.5 M to 4.5 M NaCl (Ben-Amotz and Grundwald, 1981). The species grown on salt concentrations between 0.5 to 2.5 M NaCl multiplied every 24 hour, while above 2.5 M the growth rate gradually decreased to about 1.2 at 4.5 M Nacl. Vonshak and Richmond (1981) demonstrated that Anacystis nidulans exposed for a prolonged period to a concentration of up to 0.4 M NaCl can reach a steady state of growth, while specific growth rate declined in correlation with the increase in the concentration. Brown (1982) observed exponential growth in N. bacillaris over the range of 2 to 300% artificial sea water. The species grew more rapidly at lower salinities.

In general, most euryhaline microalgae exhibit maximal growth at low salinities in the steady state. Although some species (McLachlan, 1961) showed salinity optima for growth, this was still at a salinity lower than that of full strength sea water. The behavior was attributed to the increased energy needed for ion pumping and increased requirements for reduced carbon which occur at high salinity as a consequence of osmoregulation (Brown, 1982). These increased requirements may limit growth at high salinity by limiting metabolic energy available for growth.

Steady-state photosynthetic rates seem to be less sensitive to salinity than growth rates. Broad optima for photosynthesis at various salinities were observed for P. suecica (Hellebust, 1976), A. gracilis (Ben-Amotz and Grunwald, 1981), A. nidulans (Vonshak and Richmond, 1981) and N. bacillaris (Brown, 1982), which showed significant decreases in

the specific growth rate at high salinities. The high ratio of photosynthetic rate to specific growth rate caused by high salinity was explained as an increasing demand for photosynthesis to give the same unit growth rate at high salinity (Ben-Amotz and Grunwald, 1981).

Sudden salinity changes interfere differently with cell growth and photosynthesis, depending on the existence of cell wall, because osmoregulation in walled cells involves the regulation of turgor pressure, while in naked cells which are unable to withstand significant turgor pressure, volume control is involved.

For naked cells, the downward shock from high to low salinity generally interferes more with cell growth and photosynthesis than the upward shock. The naked cells behave as osmometer and experience swelling damage following hypotonic stress (Brown, 1982). Increases in water potential owing to decreases in salinity often result in cell rupture or at least substantial increases in permeability and increased excretion, particularly in naked cells (Brown, 1985). Hypotonic lysis was found as a result of transfer from 100 to 15% seawater in M. lutheri (Craigie, 1969). Similarly, the hypotonic lysis was also observed in D. parva with the consequent inhibition of photosynthesis (Ben-Amotz and Avron, 1972). Hellebust (1976) reported that the photosynthesis inhibition in P. suecica, when high-salinity-adapted cells were transferred to low salinities, is due to a non-specific loss of soluble cell components as a result of osmotic shock causing temporary membrane leakage.

For walled cells, sudden increases in salinity generally interfere more with cell growth and photosynthesis than decreases in salinity as were shown in C. cryptica (Liu and Hellebust, 1976), Chlorella emersonii

(Setter and Greenway, 1979) and N. bacillaris (Brown, 1982). Liu and Hellebust (1976) reported that the growth inhibition in C. cryptica by the upward shock was due to temporary plasmolysis, decreased photosynthesis and increased osmolyte (poline) synthesis. The reason that the walled cells are resistant to downward shock was attributed to ability to withstand considerable turgor pressure (Brown, 1982). When an intermediate salinity step was provided, both growth and photosynthesis in N. bacillaris were enhanced (Brown, 1985). It was reported that increasing the length of the intermediate step from 10 to 120 minutes resulted in a 168-fold increase in the rate of photoassimilation of bicarbonate, while adaptation of growth took longer.

Many studies demonstrate that euryhaline microalgae can tolerate wide ranges of salinities in laboratory experiments. Even some freshwater species such as S. obliquus (Wetherell, 1963) and Ochromonas (Kaus, 1967) are known to be able to grow in saline water by the synthesis of osmolytes. However, the mass mortality of freshwater phytoplankton within the 0.10 - 1.00 o/oo mixing segment in the Tamar Estuary (Morris et al., 1978) is difficult to explain with the laboratory experiments. Filardo and Dunstan (1985) also reported sharp decrease in phytoplankton biomass within the 0 - 2 o/oo segment in the James Estuary, which was attributed to the osmotic stress encountered by the freshwater phytoplankton upon advection into the estuary. It seems somewhat of a paradox that many species can grow at various salinities in the laboratory, but they have a very narrow range of salinity for survival in nature.

Most euryhaline microalgae, in general, exhibit maximal growth at low salinities in the steady state, while photosynthetic rates are

relatively constant at various salinities. The behavior was attributed to an increasing demand for photosynthetic activity to obtain a constant growth rate at elevated salinities. This implies the existence of an energetic competition between the demand for growth and for production of osmolytes. However, metabolic conversion of starch to glycerol in A. gracilis occurred in the absense of photosynthesis and respiration (Ben-Amotz and Grundwald, 1981), while, in D. salina, oxygen evolution was stimulated by an increase in salinity (Kaplan et al., 1980). The latter was ascribed to conversion of starch to glycerol which requires photosynthetic ATP and reducing power, and results in oxygen evolution without bicarbonate assimilation. The mechanisms of energetic competition are not clearly elucidated and the fate of the metabolic conversions of osmolytes is not clear either.

Most work on photosynthesis has been done in the laboratory with a few species. It is necessary for further research to study the fluctuation of gross production caused by seasonal or long-term change of salinity in estuarine and coastal waters.

CHAPTER 2

MATERIAL AND METHODS

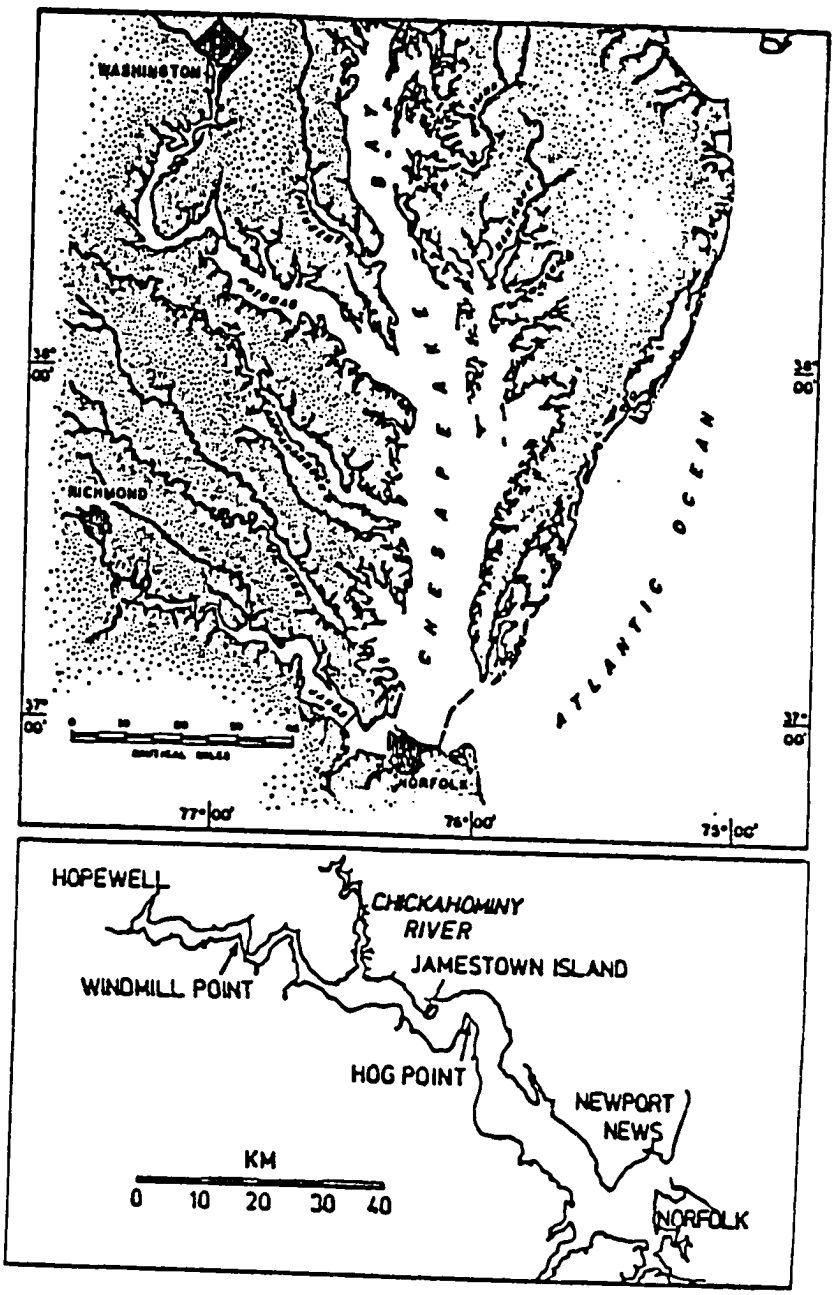
2-1 Study Area

The James River estuary (Fig. 1), the southernmost of the major rivers emptying into the western side of the Chesapeake Bay, extends the entire breadth of the State of Virginia, from its mouth at Hampton Roads to its headwaters in the Appalachian Mountains near the Virginia-West Virginia state line. The estuary follows the course of a former river valley drowned within the last 9,000 years by the most recent rise of sea level (Nichols, 1972). The floor is shaped into a central channel bordered by submerged shoals.

The James River estuary is about 640 km long and has a drainge area of approximately 21,500 km^2 (U.S. Geological Survey, 1973). It averages 3.7 m in depth at mean low water and with an average width of 6 km, has a width to depth ratio of 1620 to 1. The bottom of the estuary is sensitive to stirring by wind-induced waves (Nichols, 1972). The James River contributes about 16% of the total freshwater inflow into the Chesapeake Bay (Pritchard, 1952). The average flow (based on 37 years of record) at the fall line at Richmond is 201 m^3sec^{-1}, varying from 0.28 to 8382 m^3sec^{-1} (Fang et al. 1973). The tide is semidiurnal, having two ebbing and two flooding tides in a day, and the mean tidal range near the mouth of the James at Newport News is 0.8 m (Pritchard, 1967).

The James River receives significant artificial enrichment of nitrogen and phosphorous above the usual forest and agricultural sources.

Figure 1. The James River Estuary Study area



Approximately 2.7 metric tons of phosphorous and 8.2 metric tons of nitrogen in various organic and inorganic forms are discharged each day in the effluent of the metropolitan Richmond area. Heavy loading also occurs from Hopewell industrial and domestic sources, increasing slightly in the Hampton Roads area (Brehmer, 1972).

The James River estuary is representative of moderately stratified estuary. The salinity increases with depth, the salinity-depth curve having the general shape of an inverse tangent function (Pritchard, 1952). Superimposed on the alternating tidal motion there is a net circulation in which the upper less saline layer moves seaward and the lower more saline layer moves up the estuary. The dominant mixing agent in the estuary is turbulence caused by tidal action (Pritchard, 1967).

There are considerable seasonal variations in salinity which diminish in magnitude toward the mouth. In spring the high river flow is reflected in minimal salinities throughout the estuary, while in summer and fall the decreased river flow results in maximum salinities. In addition to the increase in salinity in a seaward direction, there is a lateral variation with lower-salinity water on the right side of the estuary, looking downstream. The longitudinal salinity gradient is approximately uniform with depth (Pritchard, 1967). The James River estuary is tidal for a distance of 170 km from its mouth and the 1.0 o/oo isohaline is normally located from 55 to 95 km upriver. The surface salinities at the mouth range from 15 to 25 o/oo (Hass, 1977).

2-2 Sampling Program and Strategies

The study area was visited at approximately one month intervals from July 1986 through August 1987 to observe the occurrence, the location, and the magnitude of the peak phytoplankton biomass. Phytoplankton biomass was determined continuously in surface water along the axial transect of the main channel from the Newport News Shipyard to the position off Hopewell city on board the R/V Linwood Holton or from the approximately 2 o/oo isohaline to the same position off Hopewell city on board the R/V ODU-1. Positions of the peaks were charted as latitude and longitude according to co-ordinates recorded on a Micrologic ML-1000 Loran C Navigator on board and buoy numbers in the channels. Salinity was measured with a Beckman RS-5 inductive salinometer when the salinity was higher than 2 o/oo, while 'Minisal' Model 2100 salinometer was used at the salinity less than 2 o/oo after water samples were brought to the laboratory. Very low salinity region was defined as the location where the surface salinity measured less than 0.5 o/oo with the "Minisal" salinometer. The peak was positioned by the distance from Newport News Shipyard and by the surface salinity measured. The magnitude of the peak was defined as the concentration of chlorophyll a at the position of maximum in vivo fluorescence.

Tidal state, amount of river discharge and nutrients were assumed as possible factors which may affect the occurrence, the position, and the magnitude of the peak phytoplankton biomass.

Monthly sampling was done at spring and neap tide in an alternating

pattern from October 1986 through February 1987, which included both periods when the peak biomass occurred and disappeared. During each cruise, sampling began at the Newport News Shipyard or the approximately 2 o/oo isohaline at the time of ebbing tide and proceeded upstream to the station off Hopewell city, and turned back at the time of flooding tide and proceeded downstream to the about 2 o/oo isohaline. Three anchor stations in total were occupied over the duration of the study, one in October 1986 at the position where biomass showed rapid increase, one in August 1987 in the vicinity of the peak biomass, and one in December 1986 when the peak biomass did not occur. The effect of the tidal state on the occurrence, the location, and the magnitude of the peak biomass was studied.

River discharge data were provided from the Virginia State Water Control Board, being collected at station 02037500 (37°33'47" N, 77°32'50" W) in James River near Richmond. River discharge influences the amount of dissolved and particulate nutrients supplied from the upstream watershed, the turbulence level and state of stratification of the water column, light penetration by virtue of the amount suspended sediment supplied, and the residence time of agal cells. The effect of river flow on the occurrence, the location, and the magnitude of the peak biomas was studied.

Samples for nutrient analyses (dissolved silicate, phosphate and nitrate) were taken from the surface water along the estuary axis. The concentration of each nutrient was plotted against surface salinity measured and the distance from the Newport News Shipyard. The distribution pattern of each nutrient during the periods that peak biomass occurred was compared qualitatively with the pattern during the

periods that peak biomass did not occur to investigate the importance of nutrients available and location of nutrient inputs in causing the observed peak biomass.

Processes hypothesized for causing the observed peak biomass were the hydrodynamic trapping, the same mechanism involved in the formation of the turbidity maximum in a partially-mixed estuary. It was also hypothesized that diatoms are selectively trapped in the turbidity maximum zone because their relatively high sinking rates closely balance the net upward vertical water velocity.

Evidences for the trapping mechanism and selective trapping of diatoms were presented. First, sinking rates of a diatom, Melosira sp, which was one of the dominant species in the peak biomass zone, were compared with the net upward vertical water velocity in the turbidity maximum zone. Second, diatom biomass in the peak zone was investigated by the percentage netplankton biomass, removal of dissolved silicate, the ratio of particulate biogenic silica to particulate organic carbon, and the ratio of particulate organic carbon to chlorophyll a. The diatom abundance in the peak zone was compared with the diatom biomass in the 2 o/oo isohaline region. Third, the peak biomass zone was matched with the turbidity maximum zone by comparing the ranges of salinity and the zones occupying the peak biomass and the turbidity maximum, respectively. The magnitude of the turbidity was measured in three different ways: the concentration of total suspended matter, the relative percentage transmission of a light beam in surface and one meter above the bottom water by using a Hydro Products' Model 612-S Transmissometer, and the light extinction coefficient calculated by light attenuation with depth. Photosynthetic light intensities in the water column were measured at

half meter intervals with a LI-185 Quantom/Radiometer/Photometer and the extinction coefficient was determined by the equation:

$$k\,(m^{-1}) = (\mathrm{Log}I^1 - \mathrm{Log}I^2)/(D^2 - D^1)$$

where

k = light extinction coefficient,

I^1, I^2 = irradiance at depth 1 and 2 in meters,

D^1, D^2 = depths of two measurements.

Phytoplankton in the shoal may grow differently from the channel and the residence time of phytoplankton in the shoals may be longer than channel, allowing phytoplankton to accumulate. The peak biomass may occur as a result of lateral dispersion from productive shoals to the main channel. The possibility of transport from lateral shoals was investigated by comparing the biomass between the channel and shoals.

Surface water samples were collected from the outflow of Turner Designs Model 10 fluorometer for nutrient analyses, measurements of extracted chlorophyll _a_, size fractionation of phytoplankton biomass, and measuring the concentrations of particulate biogenic silica, total suspended matter and particulate organic matter. Bottom water samples were collected one meter above the bottom with 8 litter General Oceanic Go Flo bottle. Temperature and salinity profiles at each station were determined at one meter intervals throughout the water column using a Beckman RS-5 Inductive Salinometer.

2.3 Field Methods

Phytoplankton Biomass

Chlorophyll a concentrations were determined by a continuous in vivo fluorescence method (Lorenzen, 1966) with a Turner Designs Model 10-000R Fluorometer equipped with a Turner F4T5/b infrared sensitive photomultiplier, a Turner 10-045 blue lamp, a CS2-64 emmision filter and a CS5-60 excitation filter, calibrated by chlorophyll a concentrations determined fluorometrically on 90% aceton extractions of cells retained on a Gelman type A-E glass fiber filter (Yentsch and Menzel, 1963; Holm-Hansen et al., 1965; Strickland and Parsons, 1972). Relative in vivo fluorescence was read at every 5 - 10 km intervals from the chart paper and it was converted to chlorophyll a concentration by multiplying the calibration factor (chlorophyll a/relative fluorescence).

Extracted chlorophyll a measurements were made on an "unfractionated" (whole sample) and a second "nanoplankton", defined as the fraction passing through a 28 um mesh Nitex net disc (Malone, 1971). Netplankton chlorophyll a was considered to be the difference between the average of replicate total chlorophyll a and the average of replicate nanoplankton chlorophyll a.

The sample filters, which had been stored frozen, were ground with a drill equipped with a serrated pestle type tissue homogenizer for one minute in 2-3 ml of 90% aceton. The suspension was subsequently transferred to a centrifuge tube and the volume taken to 10 ml with 90% aceton. The suspension was then centrifuged for 5 minutes at 4000 rpm

and the supernatant decanted into a 1 cm inside diameter cuvette.

Fluorescence before and 30 seconds after acidification (with two drops of 5% V/V HCl) was measured with the same fluorometer. Chlorophyll *a* and phaeopigment concentrations were calculated using the following equations (Strickland and Parsons, 1972):

$$\text{ug Chlorophyll a liter}^{-1} = Fd \cdot T/(T-1) \cdot (Rb-Ra)/\text{vol. filtered}$$

$$\text{ug Phaeopigments liter}^{-1} = Fd \cdot T/(T-1) \cdot (TRa-Rb)/\text{vol filtered}$$

where

Rb = Fluorescence before acidification,

Ra = Fluorescence after acidification,

T = Ratio of Rb/Ra for a phaeopigments free extract of chlorophyll a,

Fd = Appropriate calibration factor.

Fd was determined by the equation:

$$Fd = Cd / Rd$$

where

Cd = Concentration D determined spectrophotometrically,

Rd = Fluorometer response for D.

Nutrient Analyses

Samples for nutrient analyses were taken from the surface at 5 to 14 stations from July 1986 through February 1987. Samples from 1 m above the bottom were collected at 5 stations each in July 1986 and February 1987. The water was filtered on board through Gelman Type A-E glass fiber filters, stored in polyethylene bottles and frozen until the

analyses were performed.

All nutrient concentrations were determined colorimetrically by the methods of Strickland and Parsons (1972) which were modified for the Rapid Flow Analyzer (ALPKEM Corporation, 1986). With minor modifications, the method for phosphate determination is based on Murphy and Riley (1962), the method for nitrate determination on Wood et al. (1967), and the method for silicate determination on Mullin and Riley (1955).

Phosphate in the sample reacts with an acidified molybdate reagent to yield the phophomolybdate complex, which is then reduced to the intensely-colored molybdenum blue complex by the ascorbic acid. The light absorbance of the complex at 885 nm is proportional to the original phosphate concentration.

Nitrate is reduced to nitrite by the cadmium when the samples are passed through columns containing copper-coated cadmium. The reduced nitrite and original nitrite in the samples are determined by the formation of a reddish azo dye, produced by coupling diazotized sulfanilamide in an acidic solution with N-(1-Naphthyl)-Ethylenediamine. The light absorbance of the azo dye at 543 nm is proportional to the nitrite concentration. The nitrate concentration reported in this dissertation represents the nitrate plus nitrite concentrations.

Dissolved silicate in the sample reacts with a solution containing molybdate to form silicomolybdic acid. A reducing solution is then introduced which contains metol-sulfite. This reduces the silicomolybdic acid to molybdenum blue complex, whose color intensity (810 nm absorbance) is proportional to the original silicate concentration. Oxalic acid added eliminates any reduced phospho-molybdate interferences.

The detection limits which were calculated by three times the standard deviation of blanks were ± 0.05 umole/L for nitrate and phosphate and ± 1.0 umole/L for silicate methods.

Total Suspended Matter

For the determination of total suspended matter, 100 to 200 mls of water samples were filtered through pre-weighed 47 mm nuclepore filters with 0.4 um pore-size. The sample filters, which had been stored frozen, were dried for approximately 2 days at 40°C. After drying, the difference between the filter weights before and after filtering the water samples was calculated. Total suspended matter was determined by dividing the weight difference by the water volumes filtered.

Particulate Biogenic Silica

Particulate biogenic silica anaylses were performed using the sodium carbonate digestion procedure described by DeMaster (1979). Water samples (100 to 200 mls) were filtered through 47 mm nuclepore filters with 0.4 um pore-size. The sample filters, which had been stored frozen, were dried for approximately 2 days at 40°C. After drying, the filters were put in a 50-ml plastic centrifuge tubes and 1.0 ml of 30% hydrogen peroxide solution was added to each sample. The tubes were heated in a water bath at 85°C for 4 hours and then 25 ml of 0.5 Mole sodium carbonate solution was added. The material on the filter was digested for 1 hour in the water bath at 85°C. After cooling, the digestate was centrifuged at 7000 rpm for 30 minutes.

The suspension was decanted into a clean plastic graduated cylinder and diluted to 50 ml. The samples were analyzed using the colorimetric procedure for dissolved silicate determination as described above. Instead of the Rapid Flow Analyzer used for nutrient determination, spectrophotometer was used for particulate biogenic silica determination.

Particulate Organic Carbon and Nitrogen

Particulate organic carbon (POC) and nitrogen (PON) were measured with a Carlo Erba ANA 1500 NCS Analyser. Water samples (25 to 50 mls) were filtered through pre-combusted 25 mm Gelman type A-E glass fiber filters. The sample filters, which had been stored frozen, were dried for approximately 5 days at 40°C. After drying, the filters were run directly in the analyser with the catalyst.

CHAPTER 3

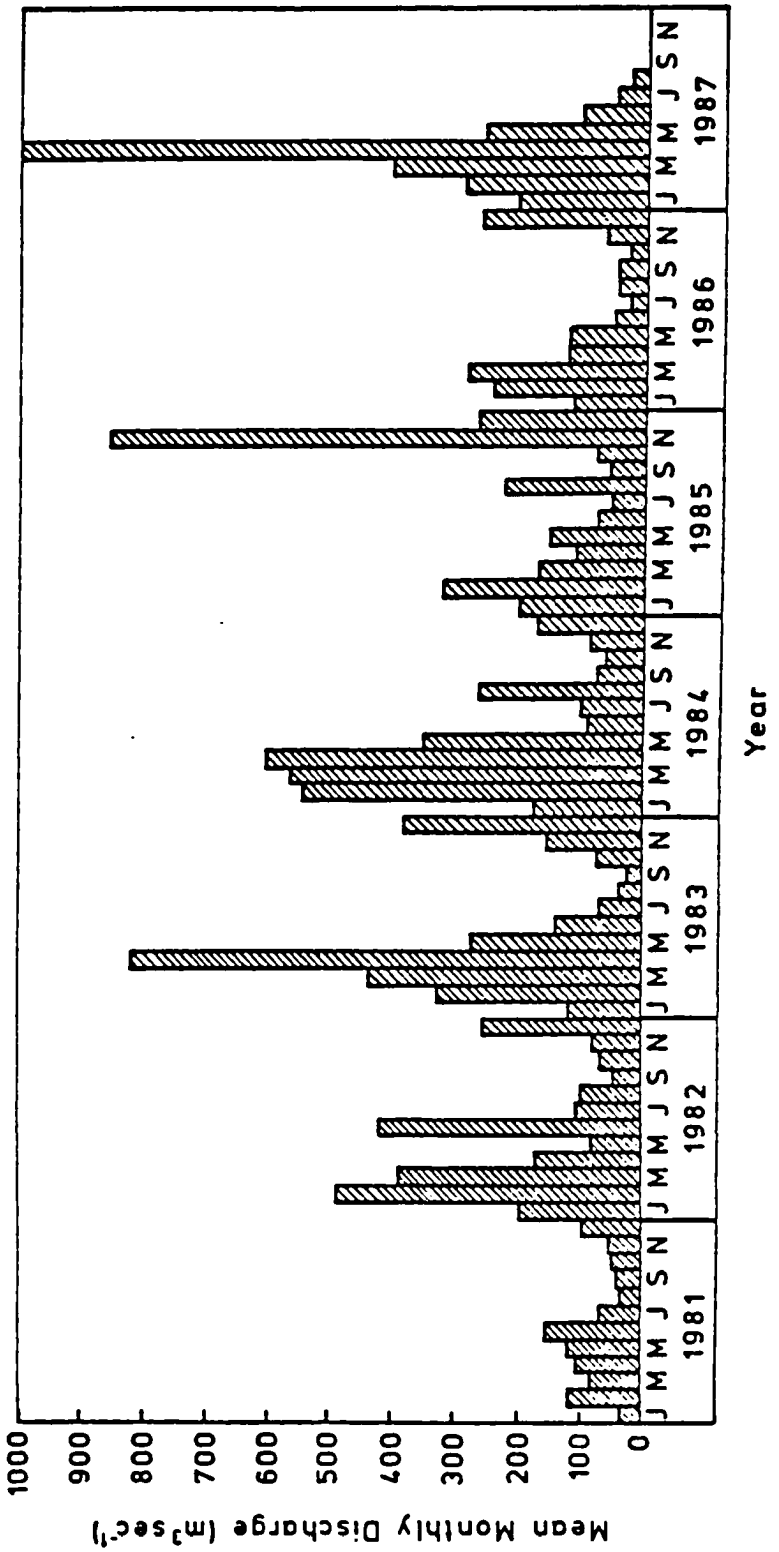
RESULTS OF FIELD STUDY

3-1 Hydrographic Data

Data for river discharge, obtained from the Virginia State Water Control Board (obtained in ft^3sec^{-1} and converted to m^3sec^{-1}), were collected at station 02037500 at mile point 116.6 in the James River. River discharge varied, over the duration of the study, from a low of 22.5 m^3sec^{-1} on 11 October 1986 to a high of 4190.9 m^3sec^{-1} on 18 April 1987. The mean monthly discharge for July through November 1986 was relatively low compared to several previous years (Fig. 2). The discharge in July was 34.4 m^3sec^{-1}, the lowest in past seven years, and then increased slightly to 70.4 m^3sec^{-1} in November. River discharge from December 1986 through March 1987 was representative of normal annual hydrography, ranging from 124.1 m^3sec^{-1} to 407.3 m^3sec^{-1}. The mean monthly discharge in April 1987 was a very high 1017.8 m^3sec^{-1}, and then it declined to relatively constant lower flows until August 1987 when the mean monthly discharge was 28.3 m^3sec^{-1}.

The surface salinity measured at the position off Newport News Shipyard(NNS) was dependent on freshwater input. It ranged from 15.3 o/oo to 25.0 o/oo except for on 21 April 1987 when the surface salinity was a very low of 2.30 o/oo as a result of abnormally high river discharge (Appendix A). Vertical profiles of salinity at NNS show an oscillation between homogeneity and stratification phenomena. The greatest difference in salinity between the surface and 1 meter above the

Figure 2. Mean monthly river discharge of the James River near Richmond during January 1981 through August 1987.



bottom was observed on 27 Februrary 1987, showing approximately a 2 o/oo difference. An homogeneous situation was observed in July and August 1987. During the course of the study, exepting April 1987, the location of the 1 o/oo isohaline extended over a distance of approximately 45 km from Hog Point to just west of Windmill Point (Appendix A). The location is comparable to the 45 km range for very low salinity regions designated by Filardo and Dunstan (1985). The water column in the very low salinity region was considered to be vertically homogeneous with respect to salinity varying less than 0.10 o/oo in all cases. The depth within this region ranged, over the course of the study, from 5 to 13 meters and was most often between 5 to 7 meters (the exception being April 1987).

Water temperature varied in response to seasonal climate. Mean surface temperature measured along the axis of the main channel ranged from 4.78°C in February 1987 to 29.57°C in July 1987 (Appendix A). Bottom temperature never varied from surface values by more than 1°C. The temperature measured in the months of December 1986 through February 1987 was less than 10°C.

3-2 Turbidity

Turbidity was measured in three different ways: (1) relative percentage transmission of a light beam measured every meter to within 1 meter above the bottom with a transmissometer (5 stations in February, 4 in June, 9 in July and 8 in August 1987); (2) the light extinction coefficient in the water column at the same stations mentioned above using a photometer; and, (3) the total suspended matter from samples taken from the surface to within 1 meter above the bottom at 5 stations in February and only from the surface at 6 stations in July and 5 stations in August 1987. The results are listed in Appendix B. Though the turbidity is known to vary over tidal cycles in relation to current speed, and to be most pronounced near the bottom (Nichols, 1972), the measurement was not synoptic with respect to the time of the day or the tidal stage.

The values of the relative percent transmission for surface and bottom waters are listed with salinity and location in Appendix B. The values from the surface of NNS were 35% in February, 42% in July and 47% in August, showing an increase with decreasing river flow. The corresponding values measured from 1 m above the bottom were 32%, 31%, and 47%, respectively. The transmissions at the position off Hopewell city remained relatively low and were independent of river flow. The values for the surface water were 12% in February, 21% in June, 10% in July and 9% in August. The corresponding values measured from 1 m above the bottom were 12%, 13%, 11% and 4%, respectively. Relatively low

values of the transmission along the estuary axis occurred each month in the upper portion, where the salinity ranged from 0.50 o/oo to 7.68 o/oo. The range is comparable to that of 0.5 - 2.0 o/oo, the landward limit of the James River turbidity maximum reported by Feuillet and Fleischer (1980). The values measured from 1 m above the bottom within this portion were much lower than those measured from the surface water. While the values from the surface ranged from 5.3% to 28%, the values from 1 m above the bottom ranged from 1.0% to 11.0%.

Figure 3 shows relative percentage transmission measured from the surface in February through August 1987. The highest turbidity (the lowest transmission) occurred in February when river flow was highest. As river discharge decreases, the turbidity maximum zone moves landward and the magnitude of the turbidity decreases. Nichols (1972) also indicated that the turbidity maximum in the James River estuary persists most of the year, being most pronounced in the spring when river flow is high and weak in the fall when flow is low.

Light extinction coefficient ranged from 1.19 at NNS on 12 August 1987 to 7.42 in the 0.78 o/oo isohaline on 27 February 1987 (Appendix B). The coefficient was inversely proportional to the relative percentage transmission measured by transmissometer ($n = 22$, $r = -0.8544$) as shown in Figure 4. Relatively higher values occurred each month in the upper portion of the estuary, and the values decreased with decreasing river discharge. The compensation depth at which the photosynthesis of a cell is equal to its respiration was defined by the depth of 1% surface irradiance. The compensation depth at NNS was 2.5 meters in February and increased steadily to 3.9 meters in August. At Hopewell city, the compensation depth varied from 1.2 to 2.0 meters. The compensation depth

Figure 3. The relative percentage transmission measured from the surface water along the estuary axis in February through August 1987.

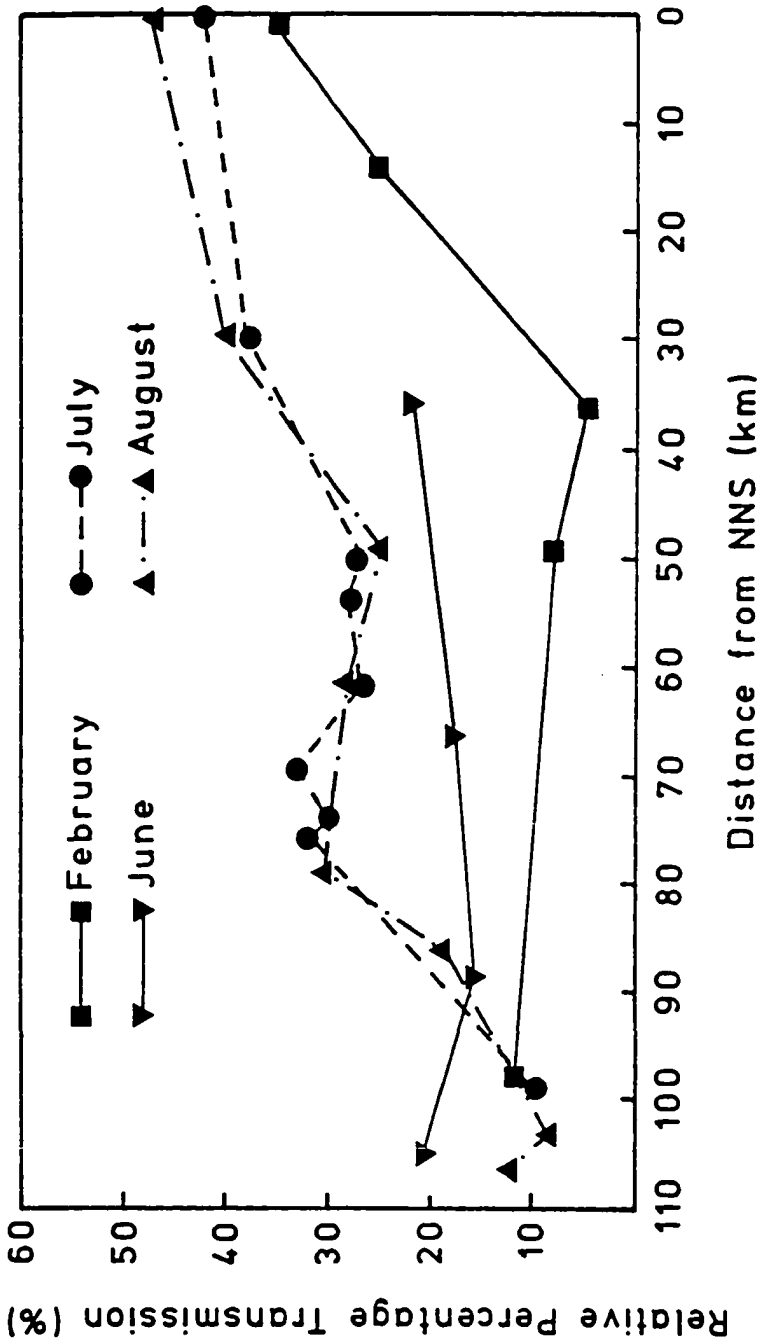
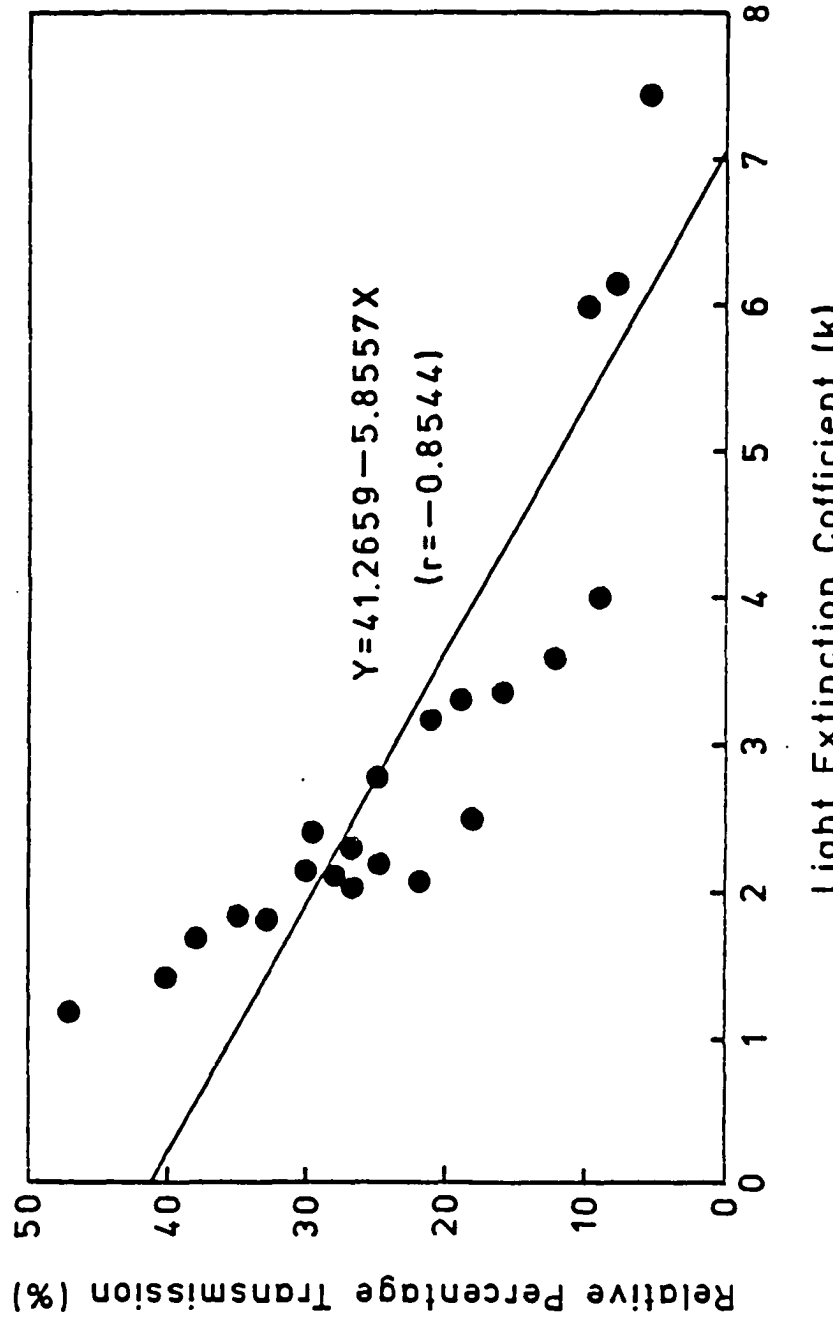


Figure 4. The relationship between the relative percentage transmission and the light extinction coefficient.

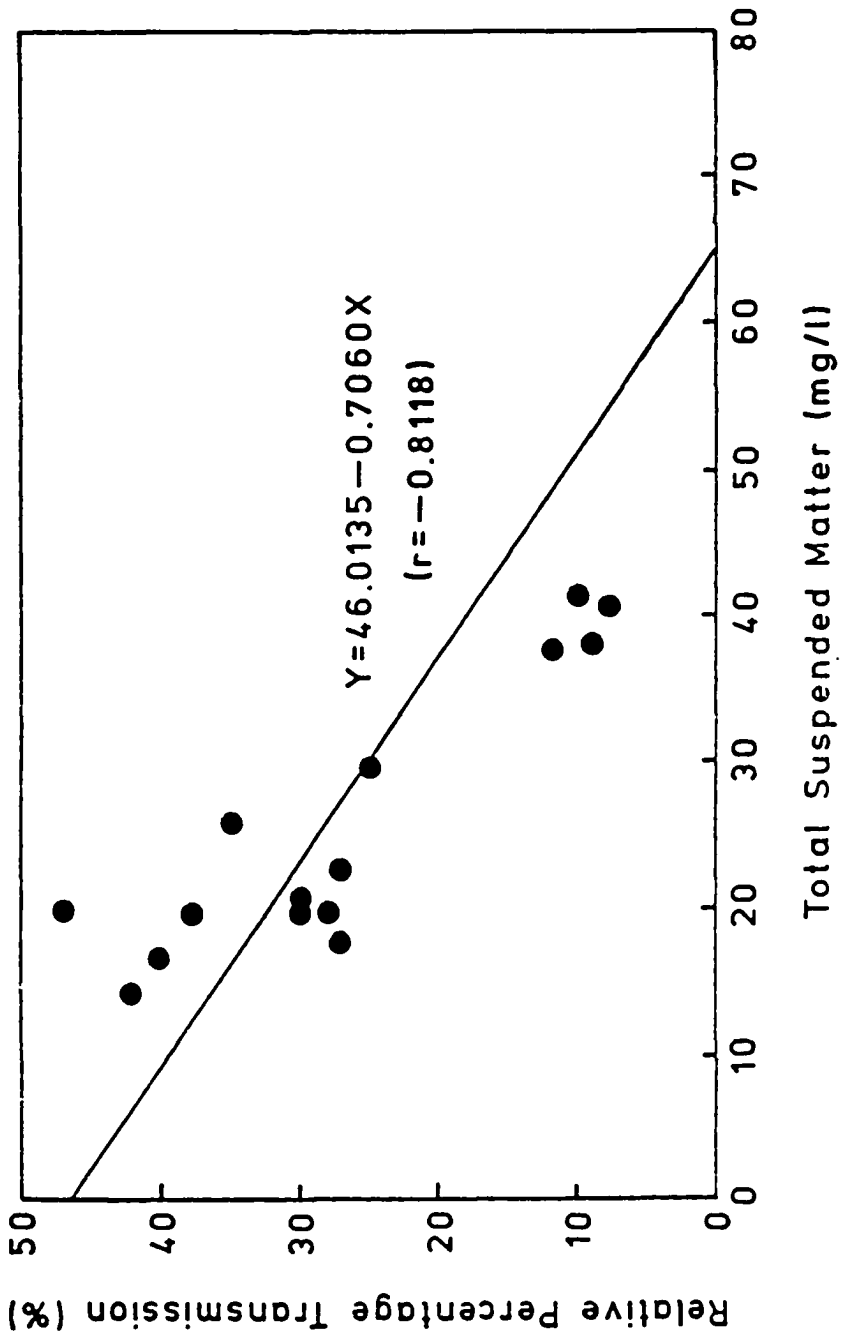


in the upper portion of the estuary (the turbidity maximum zone) was shallowest in February (less than 0.8 meter) and deepest in August (approximately 2 meter).

Total suspended matter ranged from 14.1 mg/L at NNS on 15 July 1987 to 74.9 mg/L in the 0.78 o/oo isohaline on 27 February 1987 (Appendix B). The concentration was relatively high in February but low in July and August. Though the transmission is known to vary with the particle size and shape (Baker and Lavelle, 1984), the relative percentage transmission in this study was an inversely linear function of the total suspended matter. The slope was -0.482 in February ($n = 5$, $r = -0.7554$), and it decreased to -1.066 in July ($n = 6$, $r = -0.9085$) and -1.449 in August ($n = 5$, $r = -0.8584$). However, the two slopes between February and August were not significantly different ($t = 2.447$, $0.10 < P < 0.20$). The combined relationship between the relative percentage transmission and the total suspended matter for three months is drawn in Figure 5, the slope being -0.706 ($n = 16$, $r = -0.8118$).

In summary, as river discharge increased, the turbidity maximum zone moved in the seaward direction and the magnitude of the turbidity increased.

Figure 5. The relationship between the relative percentage transmission and the total suspended matter.



3-3 Phytoplankton Biomass

The spatial distribution of chlorophyll a versus distance from a fixed station located off Newport News Shipyard (NNS) for the surface waters are depicted graphically with salinity in Appendix C. These data which were collected at approximately one month intervals represent the distribution of chlorophyll a along the main channel of the river from NNS or approximately the 2 o/oo isohaline to the position off Hopewell city, located about 110 km upstream from NNS.

From July through December 1986, surface phytoplankton chlorophyll a ranged from 1.48 ug/L on 20 December to 87.49 ug/L on 25 July. July through November have chlorophyll a peaks in the very low salinity region. In July chlorophyll a was relatively low and constant from NNS to the 1.70 o/oo isohaline (69.0 km upstream). The concentration increased rapidly from the 1.70 o/oo isohaline and peaked in the 0.12 o/oo isohaline (102.5 km upstream) as 87.49 ug/L. It decreased sharply in the freshwater zone. A similar pattern of chlorophyll a distribution occurred in October. The concentration was low and constant in mid and down estuary and increased rapidly from the 1.52 o/oo isohaline (76.8 km upstream). It peaked in the 0.17 o/oo isohaline (100.6 km upstream) as 78.61 ug/L, and then decreased sharply. A similar peak also occurred in November. Chlorophyll a increased rapidly from the 1.54 o/oo isohaline (67.5 km upstream) to the 0.18 o/oo isohaline (89.1 km upstream) where the chlorophyll a concentration was 40.65 ug/L. It decreased rapidly in the freshwater zone. At the position off Hopewell city, the chlorophyll

a in November was a low of 6.92 ug/L, while it was 70.48 ug/l in July. The peak disappeared in December, chlorophyll a ranging from 1.48 ug/L to 5.23 ug/L.

A composite plot of chlorophyll a (July through December 1986) is shown in Figure 6. From July to November 1986, maximum chlorophyll a decreased from 87.49 ug/L to 40.65 ug/L and the location of the peak moved 13.4 km downstream. The width of the peak zone also decreasd, being approximately 62 km in July, 48 km in October and 44 km in November. The peak did not occur in December and chlorophyll a was low in the entire estuary including the freshwater zone.

By April 1987, chlorophyll a in the very low salinity region and in the freshwater zone did not develop, ranging from 1.50 ug/L on 21 January to 11.69 ug/L on 21 April (Appendix C). In February there was a phytoplankton bloom at the NNS with 49.79 ug/L chlorophyll a. The bloom disappeared by April and chlorophyll a at the NNS remained relatively low through the final sampling in August 1987. High phytoplankton biomass (61.35 ug/L of chlorophyll a) in the very low salinity region occurred in June. The high biomass remained relatively constant in the freshwater zone compared to the biomass decrease in this zone during the summer and autumn of 1986. The concentration of chlorophyll a in the very low salinity region increased to 97.69 ug/L in July and 114.21 ug/L in August. There was a rapid decrease in the concentration of chlorophyll a in the freshwater zone during August. The phytoplankton biomass in the summer of 1987 was higher than the biomass in the summer of 1986.

Maximum concentration of chlorophyll a in the peak region and its position by the distance from NNS, measyrements of surface salinity are summarized in Table 1. The peak biomass occurred between 89.1 and 102.5

Figure 6. Phytoplankton biomass from the surface water along the estuary axis in July through December 1986.

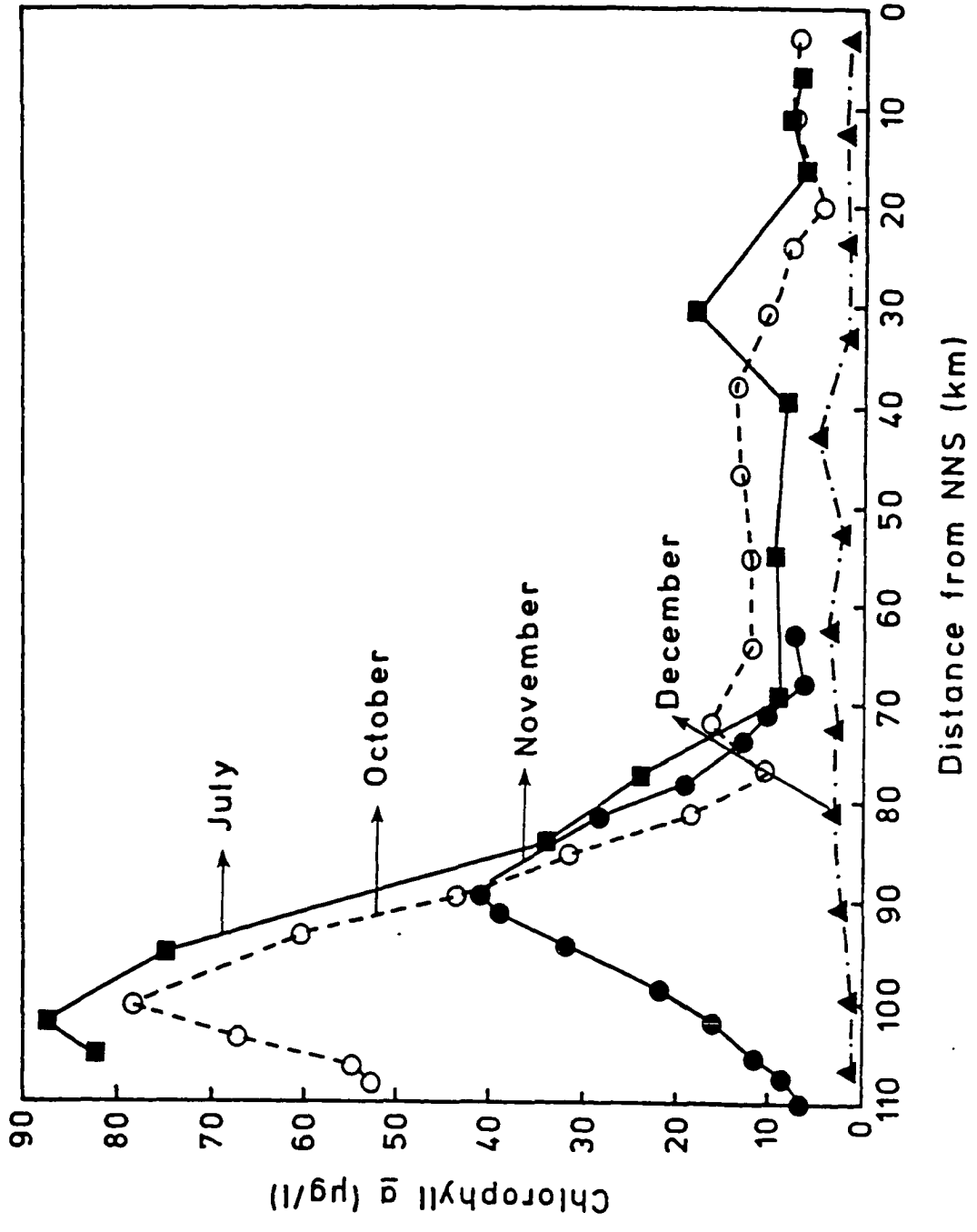


Table 1. Maximum surface phytoplankton biomass in the peak region and its position by the distance from Newport News Shipyard and surface salinity measured (D = distance from NNS and S = salinity).

Month	D (km)	S (o/oo)	Chlorophyll a (ug/L)
July 1986	102.4	0.12	87.49
October 1986	100.6	0.17	78.61
November 1986	89.1	0.16	40.65
June 1987	99.0	0	61.35
July 1987	98.8	0.06	97.69
August 1987	101.4	0.11	114.21

km from NNS. The salinity at which peak biomass occurred is almost the same in each month, ranging from 0 to 0.17 o/oo isohaline. This suggests that the location of the peak biomass is dependent on the amount of river discharge.

Figure 7 shows that surface phytoplankton chlorophyll a is inversely related to the river discharge and high phytoplankton biomass in the very low salinity region occurs only when mean monthly discharge is less than 112 m^3sec^{-1}. When the discharge was less than 112 m^3sec^{-1}, maximum chlorophyll a concentration was plotted against mean monthly river discharge (Fig. 8). Both in 1986 and 1987, the biomass decreased with increasing river discharge. The slope was -1.2173 ($n = 3$, $r = -0.9912$) and -0.6395 ($n = 3$, $r = -0.9999$) in 1986 and 1987, respectively. The two slopes are significantly different ($t = 4.567$, $0.02 < P < 0.05$). Phytoplankton biomass was higher in 1987 than in 1986. Excellent linearity in each year and significant different slope between two years suggest that river discharge plays an important role in determining the biomass in the very low salinity region in a year, but the biomass in each year is determined by other factors in addition to the amount of river discharge. When river discharge was more than 112 m^3sec^{-1}, the phytoplankton biomass peak disappeared in the very low salinity region (Fig. 7).

When river discharge increased, surface phytoplankton biomass in the very low salinity region decreased (Fig. 8), but the magnitude of the turbidity maximum increased (Fig. 3). Therefore, surface biomass is inversely related to the magnitude of the turbidity maximum. Figure 9 shows the linear relationship between surface phytoplankton chlorophyll a in the very low salinity region and the relative percentage transmission

Figure 7. The relationship between maximum phytoplankton biomass in the very low salinity region and mean monthly river discharge.

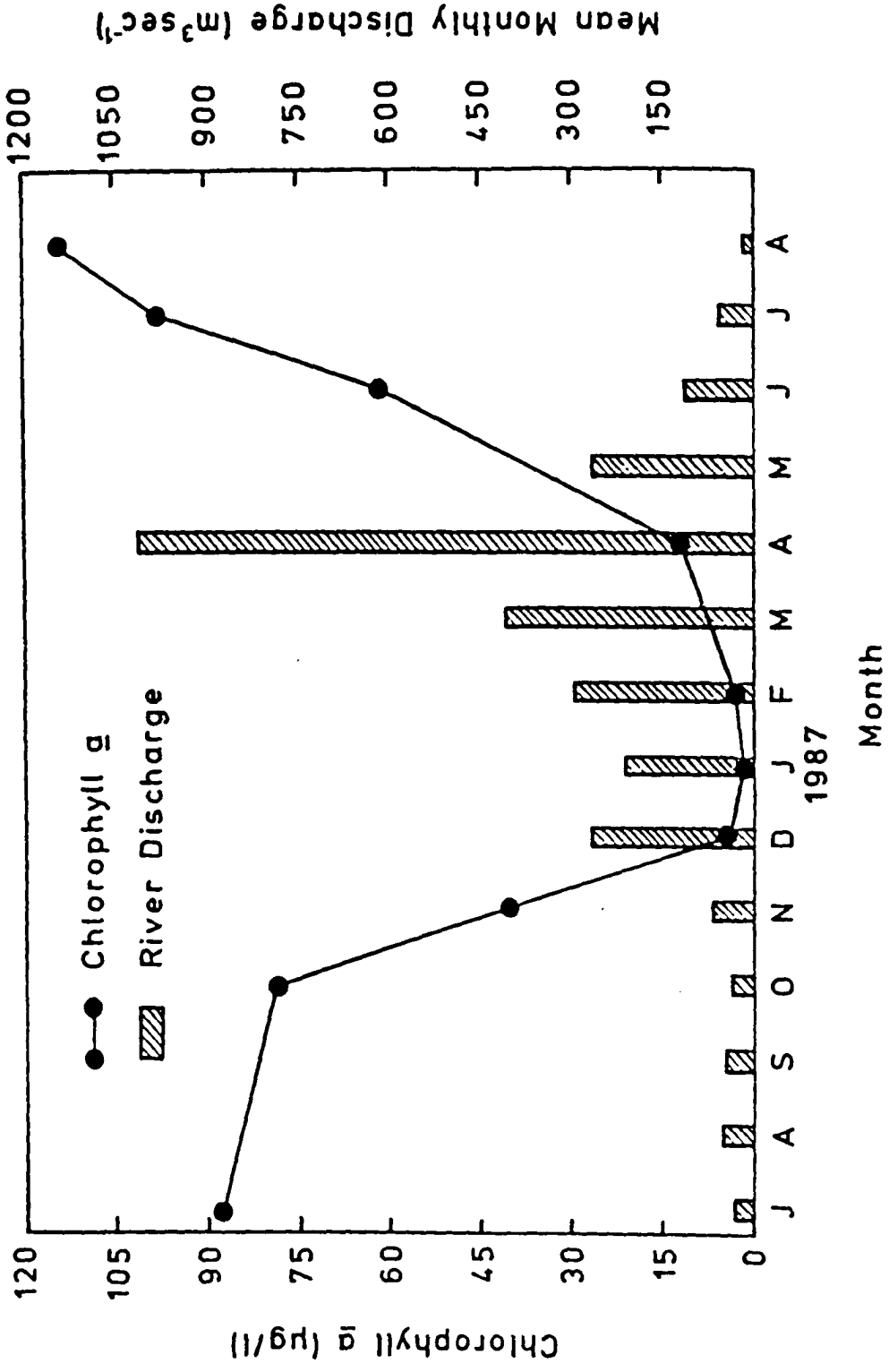


Figure 8. The plotting of maximum phytoplankton biomass in the very low salinity region against mean monthly river discharge in 1986 and 1987 when peak biomass occurred.

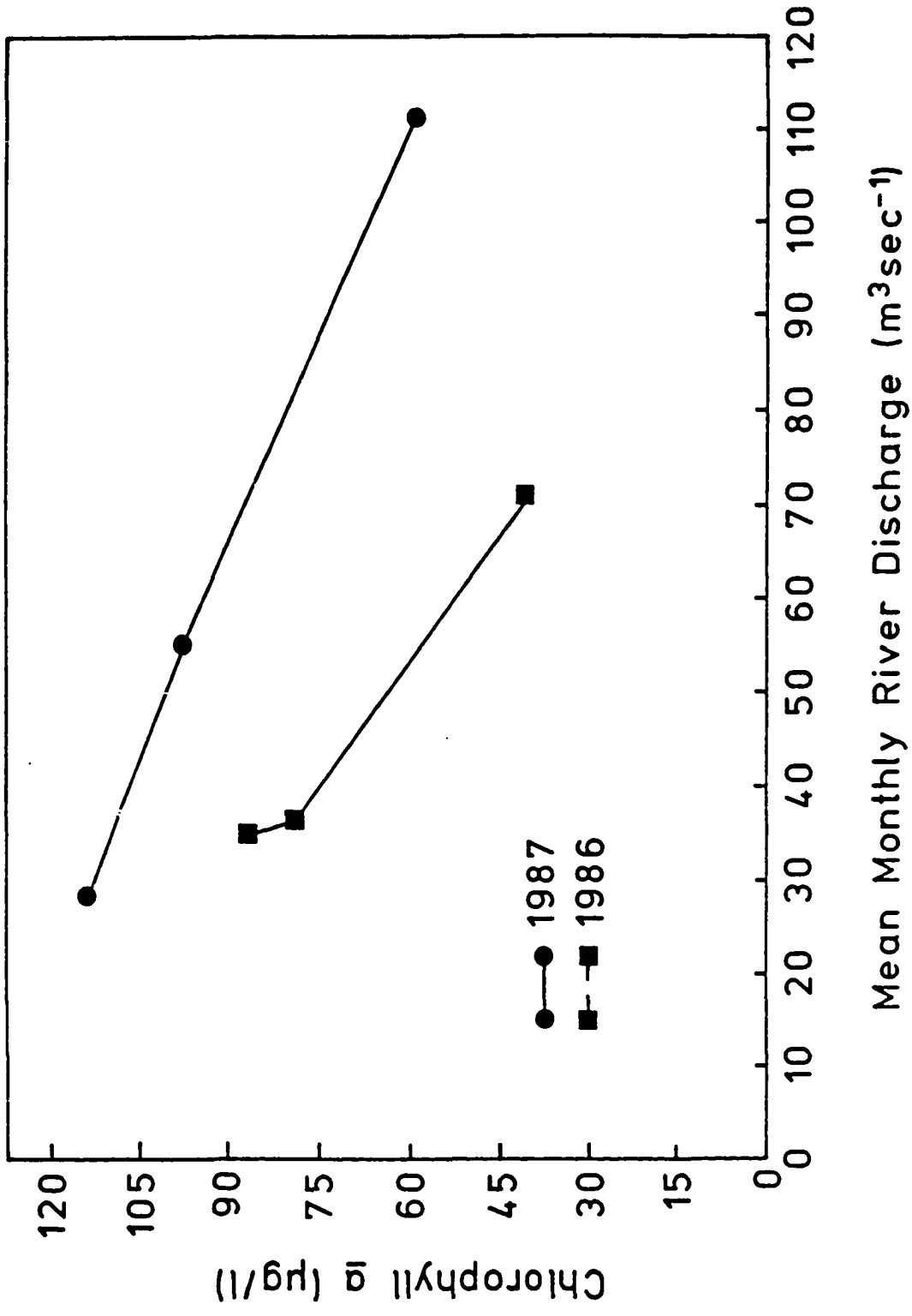
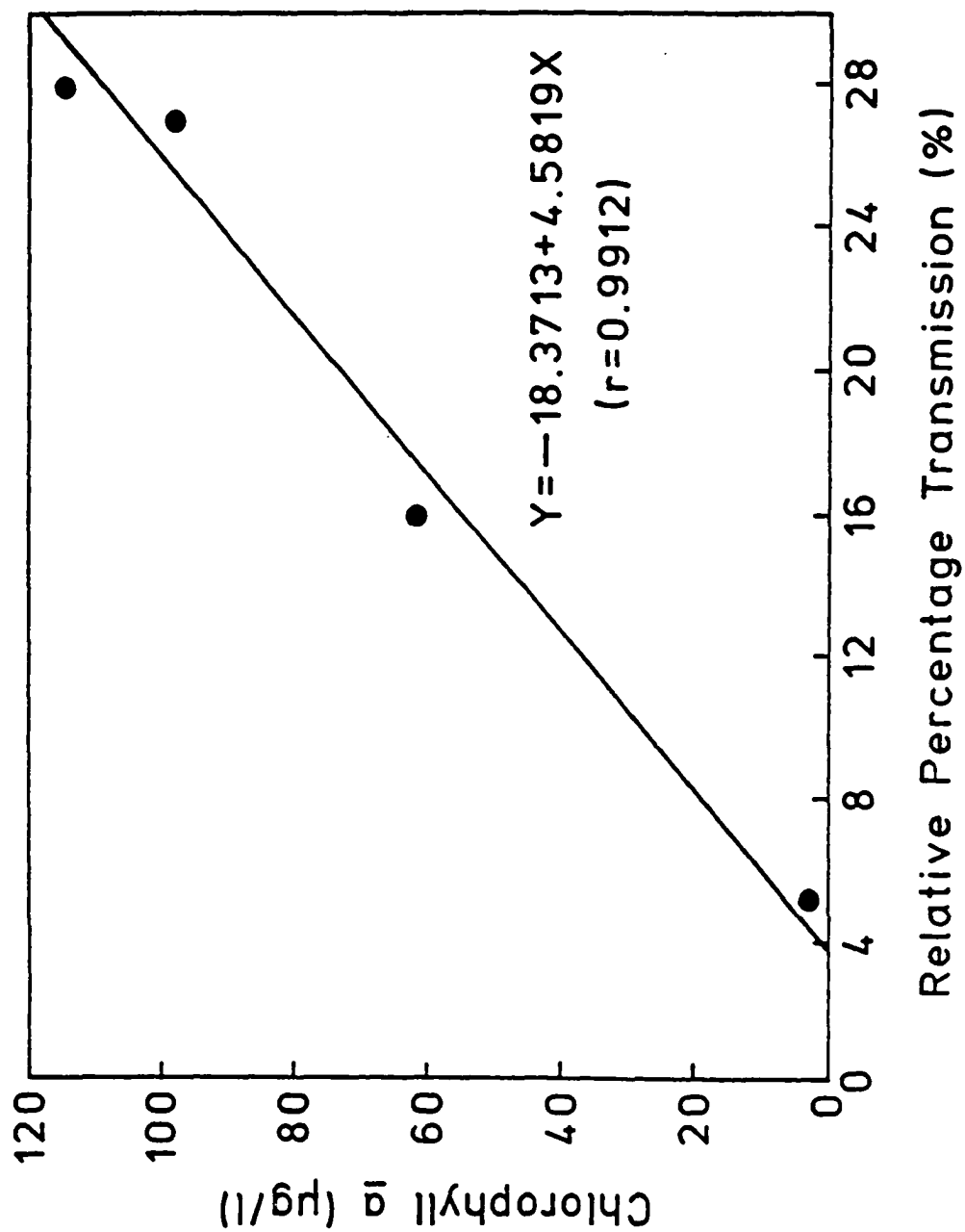


Figure 9. The relationship between maximum phytoplankton biomass in the very low salinity region and relative percentage transmission in the turbidity maximum zone.



in the turbidity maximum zone. As the transmission increased (as the turbidity decreased), phytoplankton biomass increased.

Netplankton chlorophyll a collected for July 1986 through August 1987, comprised 0 to 73% of the biomass in the very low salinity region and accounted for 0 to 25% of the biomass in 2 o/oo water (Fig. 10). During the time of the year when the phytoplankton biomass peak occurred (summer and autumn), the percent netplankton chlorophyll a in the very low salinity region averaged 35%, which is significantly higher than the percent at the 2 o/oo isohaline ($t = 2.81$, $0.005 < P < 0.01$). However, during winter and spring when the peak did not occur, the percent netplankton chlorophyll a in the very low salinity region decreased to 7% average, which is not significantly different from the value at the 2 o/oo isohaline. When the spring phytoplankton bloom occurred in February 1987 at NNS, the percent netplankton was 80% of the total biomass. In June 1987, the percent netplankton biomass was 73% at the first appearance of high phytoplankton biomass in the very low salinity region.

Surface phytoplankton chlorophyll a data over the tidal cycle were collected in three anchor stations over the duration of the study and the results of the biomass fluctuation with time of day are presented in Table 2. The surface salinity in October 1986, which was measured at Dancing Point (approximately 61 km upstream from NNS), ranged from 3.86 to 5.60 o/oo and the salinity measured at 1 meter above the bottom ranged from 4.10 to 6.04 o/oo. Surface phytoplankton chlorophyll a ranged from 9.67 to 23.49 ug/L. Two peaks were observed during the ebbing tide. The surface salinities at two peaks were 4.32 and 4.68 o/oo, respectively. In December 1986 (data collected at Dancing Point, 61 km upstream from NNS), the salinity ranged from 0.56 to 1.80 o/oo in the surface and 0.64

Figure 10. Percentage netplankton biomass in the very low salinity region and at the approximately 2 o/oo isohaline.

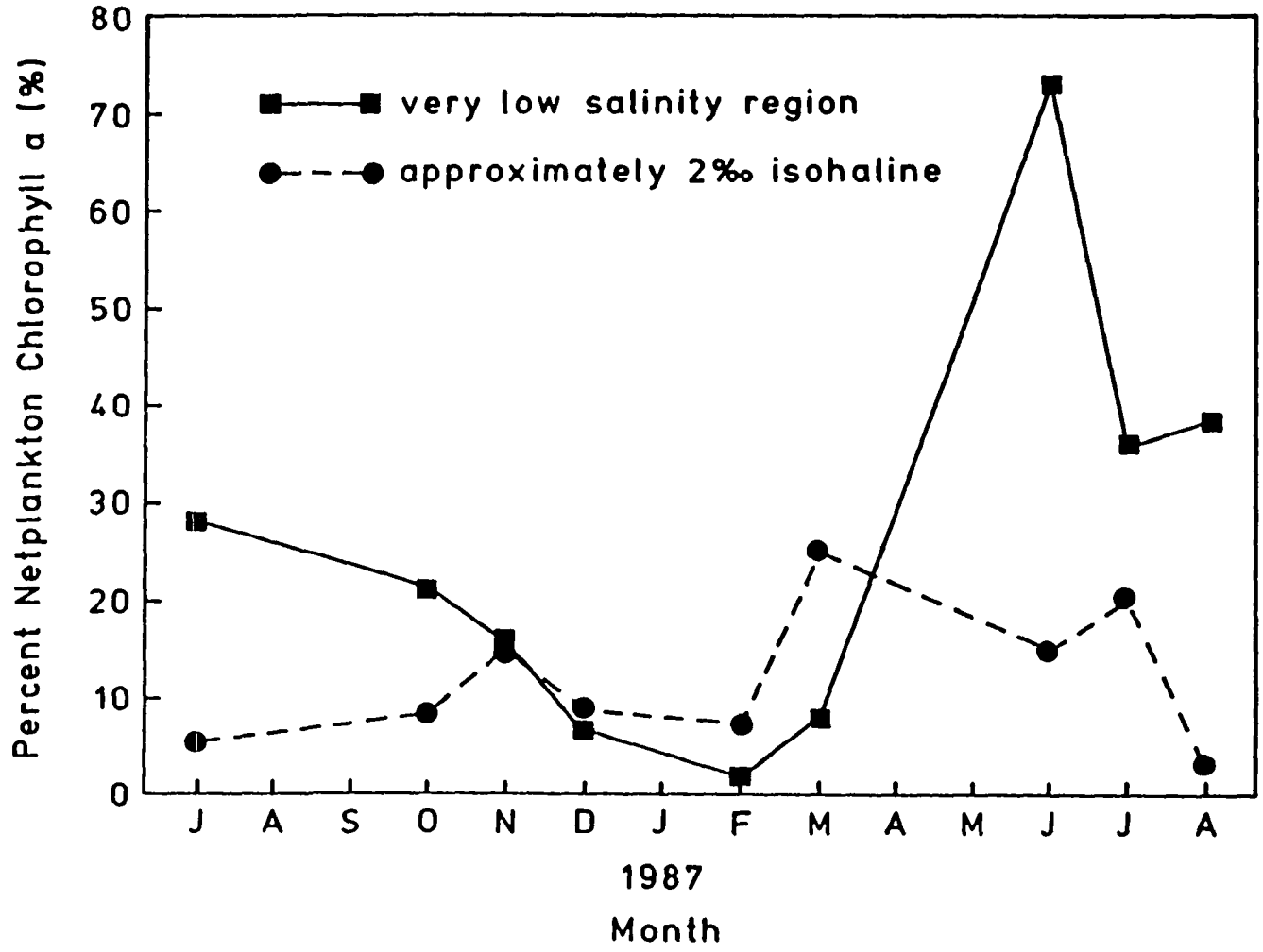


Table 2. Surface phytoplankton biomass over the tidal cycle at anchor stations in October and December 1986, and August 1987 (Data in October and December were collected 61 km upstream from NNS and data in August 93 km upstream).

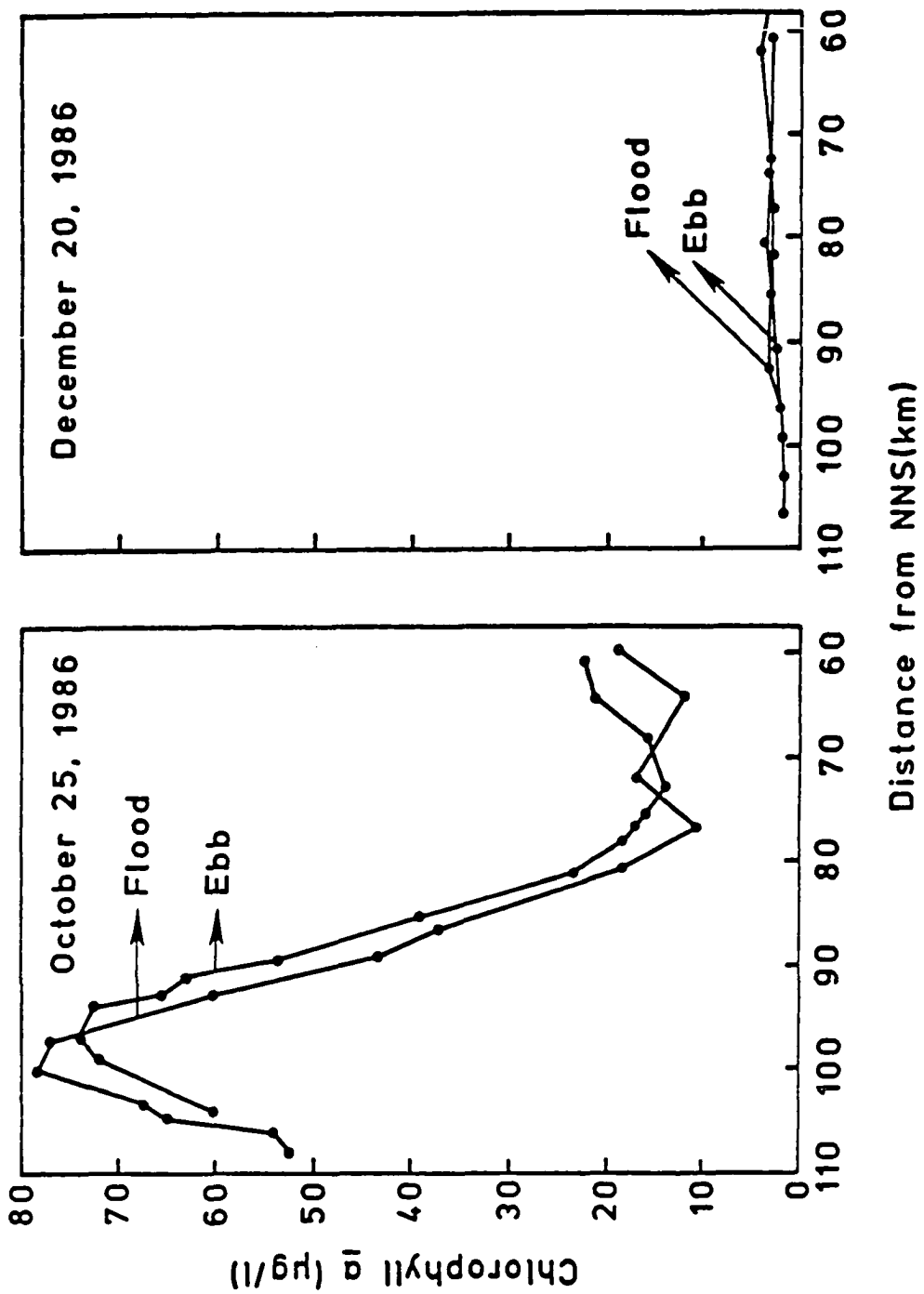
Time	Chlorophyll *a* (ug/L)			Surface Salinity		Bottom Salinity	
	Oct.	Dec.	Aug.	Oct.	Dec.	Oct.	Dec.
1730	-	3.04	-	-	1.80	-	2.15
1800	23.49	-	96.22	4.32	-	5.34	-
1830	-	3.36	-	-	1.50	-	1.70
1900	17.01	-	96.22	5.14	-	5.82	-
1930	-	3.46	-	-	1.12	-	1.17
2000	12.17	-	91.97	5.60	-	5.96	-
2030	-	3.80	-	-	1.00	-	1.13
2100	11.69	-	91.97	5.24	-	6.00	-
2130	-	4.23	-	-	0.74	-	0.87
2200	11.21	-	96.20	5.50	-	5.66	-
2230	-	4.23	-	-	0.93	-	1.02
2300	13.04	-	99.66	5.76	-	6.04	-
2330	-	4.66	-	-	0.77	-	0.94
2400	17.78	-	100.05	4.68	-	5.60	-
0030	-	4.18	-	-	0.56	-	0.64
0100	15.58	-	101.97	4.52	-	5.30	-
0130	-	3.99	-	-	1.02	-	1.17
0200	11.91	-	-	4.20	-	4.84	-
0230	-	3.67	-	-	1.34	-	1.76
0300	10.70	-	91.39	3.86	-	4.98	-
0330	-	3.38	-	-	1.43	-	1.47
0400	10.24	-	92.35	4.35	-	4.70	-
0430	-	3.24	-	-	1.50	-	1.65
0500	9.67	-	87.54	4.30	-	4.90	-
0530	-	2.97	-	-	1.60	-	1.85
0600	11.86	-	86.58	4.30	-	4.10	-

to 2.15 o/oo at 1 meter above the bottom. Maximum chlorophyll a was 4.66 ug/L with 0.77 o/oo of surface salinity and minimum was 2.97 ug/L with 1.60 o/oo. In August 1987, data were collected near the position where the phytoplankton biomass peak occurred (approximately 93.1 km upstream from NNS). Surface phytoplankton chlorophyll a ranged from 86.58 to 101.97 ug/L. In October, December and August, the differences between maximum and minimum chlorophyll a were 13.82 ug/L, 1.69 ug/L and 15.39 ug/L, respectively.

Figure 11 shows the surface chlorophyll a along the main channel during periods of flooding and ebbing tides for one day. During the October 1986 survey, maximum chlorophyll a during periods of flooding tide was 78.61 ug/L at the position off Hopewell city (100.6 km upstream from NNS) and the concentration at the same position decreased to 69.93 ug/L during ebbing tide. The difference of 8.98 ug/L is comparable to 15.39 ug/L of difference between maximum and minimum chlorophyll a concentration measured over one tidal cycle at the anchor station near the peak in August 1987. Maximum chlorophyll a concentration during periods of ebbing tide was 74.23 ug/L and occurred approximately 3 km downstream. The difference in chlorophyll a concentration between the two peaks was 4.38 ug/L but the the peak zones were almost equal in width. In December 1986, when the peak did not occur, there was little diffrence in chlorophyll a concentration between the flooding and ebbing tide period.

The cycle of spring - neap tide did not affect the occurrence of peak phytoplankton biomass in the very low salinity region. Monthly sampling was done at spring and neap tide period in an alternating pattern from July 1986 through February 1987. The peak biomass occurred

Figure 11. Surface phytoplankton biomass during the periods of flooding and ebbing tide for one day on 25 October and on 20 December 1986.



in July through November 1986 independent of the tidal state. From December 1986 through February 1987, peak biomass disappeared without regard to the tidal state.

3-4 Particulate Organic Matter

Particulate organic carbon (POC) and nitrogen (PON), particulate biogenic silica (PBS), chlorophyll a and phaeopigments were measured in the surface water along the estuary axis. The ratios of POC to PON, chlorophyll a to phaeopigments, PBS to POC, POC to chlorophyll a, and the percent dry weight of POC, PON, PBS and chlorophyll a in total suspended matter were calculated. The results are recorded in Appendices D, E and F. This study focused on the comparison of the chemical compositions of these particulate organic matters between the zone of peak phytoplankton biomass and approximately 2 o/oo isohaline region.

Particulate biogenic silica (PBS) in the surface was usually less than 1 umole/L except in the zone of high phytoplankton biomass (Table 3). When there was a phytoplankton bloom at the mouth of the estuary in February 1987, the concentration was 8.65 umole/L. The concentration in the peak biomass zone in July and August 1987 was 20.07 and 16.26 umole/L, respectively. These values are much lower than the inflowing riverine dissolved silicate concentration (approximately 150 umole/L). The dry weight ratio of PBS to particulate organic carbon (POC) ranged from undetectable levels to 0.213 (Table 3). During July and August 1987 when peak biomass occurred in the very low salinity region, the mean ratio in the peak biomass zone was 0.181, while the ratio averaged 0.008 in the 2 o/oo isohaline region (Table 4). Particulate biogenic silica (PBS) comprised 0.004 to 2.937% of the total suspended matter by dry weight (Table 5). The percent PBS in the peak biomass zone averaged

Table 3. Concentration of particulate biogenic silica (unit = umole/L) and the dry weight ratio of particulate biogenic silica (PBS) to particulate organic carbon (POC) from the surface water along the estuary axis.

February 27, 1987

D (km)	S (o/oo)	Concentration (umole/L)	PBS/POC
0.8	15.32	8.65	0.213
13.9	7.70	0.10	0.002
36.6	0.78	0.05	ND
47.6	0.02	0.05	ND

July 19, 1987

D (km)	S (o/oo)	Concentration (umole/L)	PBS/POC
29.3	7.68	0.25	0.006
49.7	2.36	0.46	0.006
61.7	-	0.35	0.009
74.1	-	0.56	0.009
98.8	0.06	20.07	0.187

August 12, 1987

D (km)	S (o/oo)	Concentration (umole/L)	PBS/POC
61.3	3.05	0.35	0.006
102.9	0.06	16.26	0.175

Table 4. Comparison of mean values of the POC/PON ratio by atom, the ratio of POC to chlorophyll a (POC/chl.a), the Rb/Ra ratio (Rb = fluorescence before acidification, Ra = fluorescence after acidification), the ratio of PBS (particulate biogenic silica) to POC and percent dry weight of chlorophyll a, POC, PON and PBS in total suspended matter between the peak biomass zone and 2 o/oo isohaline region when peak biomass occurred in the very low salinity region (Data are mean ± standard deviation, with number of observations in parentheses).

Characteristics	Peak Zone	2 o/oo Isohaline
POC/PON	9.86 ± 1.32 (4)	18.58 ± 4.64 (4)
POC/chl.a	62.00 ± 7.40 (4)	146.08 ± 43.08 (4)
Rb/Ra	1.90 ± 0.008 (6)	1.73 ± 0.115 (6)
PBS/POC	0.181 ± 0.008 (2)	0.008 ± 0.002 (2)
% chl.a	0.27 ± 0.035 (2)	0.12 ± 0.057 (2)
% POC	15.21 ± 0.71 (2)	17.89 ± 0.53 (2)
% PON	1.74 ± 0.34 (2)	1.41 ± 0.27 (2)
% PBS	2.756 ± 0.257 (2)	0.114 ± 0.011 (2)

Table 5. Percent dry weight of chlorophyll a, particulate biogenic silica (PBS), particulate organic nitrogen (PON) and carbon (POC) in total suspended matter in February, July and August 1987 (D = distance from NNS, S = surface water salinity and unit = %).

February 27, 1987

D (km)	S (o/oo)	% Chl.a	% PBS	% PON	% POC
0.8	15.32	0.19	2.011	0.69	9.44
13.9	7.70	0.05	0.020	0.28	9.47
36.6	0.78	0	0.004	ND	4.52
49.6	0.02	0.01	0.008	ND	5.32

July 15, 1987

D (km)	S (o/oo)	% Chl.a	% PBS	% PON	% POC
29.3	7.68	0.06	0.076	0.95	13.59
49.7	2.36	0.08	0.122	0.83	10.30
61.7	-	0.18	0.121	1.39	19.64
74.1	-	0.17	0.110	1.22	18.26
98.8	0.06	0.24	2.937	1.98	15.71

August 12, 1987

D (km)	S (o/oo)	% Chl.a	% PBS	% PON	% POC
61.3	3.05	0.16	0.106	1.60	17.51
102.9	0.06	0.29	2.574	1.49	14.71

2.76%, while the percent decreased to 0.11% in the 2 o/oo isohaline region (Table 4).

Chlorophyll a comprised from 0 to 0.29% of the total suspended matter by dry weight (Table 5). When peak phytoplankton biomass occurred in the very low salinity region, the percent averaged 0.27% in the peak biomass zone, while the percent decreased to 0.12% in the 2 o/oo isohaline region (Table 4). The ratio of particulate organic carbon (POC) to chlorophyll a are recorded in Appendix D. The ratio ranged from 48.9 to 998.8. The relatively low ratio in each month occurred in the high biomass zone. In February 1987 when there was a phytoplankton bloom at the mouth of the estuary, the ratio was 48.9. During the periods that the peak biomass occurred in the very low salinity region, the mean ratio in the peak zone (Table 4) was 62.0, which is significantly lower than the mean ratio of 146.1 in the 2 o/oo isohaline region ($t = 3.848$, $0.005 < P < 0.01$).

The ratios of fluorescence values before acidification to fluorescence after acidification of extracts (ratio of chlorophyll a to phaeopigments) from the surface water along the estuary axis are recorded in Appendix E. The ratio ranged from 1.23 at the 0.78 o/oo isohaline on 27 February 1987 to 2.09 at the 5.88 o/oo isohaline on 25 October 1986. Relatively low values in each month usually occurred in the upper portion of estuary, where the magnitude of the turbidity was high. Table 6 shows monthly ratios from the surface water of the very low salinity region. In the summer and fall of 1986 when river discharge and the magnitude of the turbidity were low, the ratio was relatively high (ranging from 1.88 to 1.89), and then declined to lower values (ranging 1.26 to 1.51) during winter 1986 and early spring 1987. In the late spring and summer of

Table 6. Monthly ratio of fluorescence values before acidification (Rb) to fluorescence after acidification (Ra) of extracts from the surface water of the very low salinity region (less than 0.5 o/oo).

Month	Rb/Ra
July 25, 1986	1.89
October 25, 1986	1.89
November 24, 1986	1.88
December 20, 1986	1.48
January 21, 1987	1.31
February 27, 1987	1.26
April 1, 1987	1.51
April 21, 1987	1.65
June 19, 1987	1.90
July 15, 1987	1.91
August 12, 1987	1.90

1987, the ratio increased again to 1.91. When the phytoplankton biomass peak occurred in the very low salinity region, the ratio averaged 1.90 in the peak biomass zone (Table 4). This value is significantly higher than the mean value of 1.73 in the 2 o/oo isohaline zone during corresponding periods ($t = 3.602$, $0.002 < P < 0.005$).

Particulate organic carbon (POC) and nitrogen (PON), particulate biogenic silica (PBS) and the ratio of POC to PON by atom are recorded in Appendix F. Particulate organic carbon (POC) ranged from 0.7 mg/L near the estuary mouth on 25 July 1986 to 6.4 mg/L at the 0.06 o/oo isohaline on 15 July 1987. Particulate organic nitrogen (PON) ranged from undetectable levels in the upper portion of estuary on 27 February 1987 to 0.81 mg/L at the 0.06 o/oo isohaline on 15 July 1987. The ratio of POC to PON by atom ranged from 8.48 at the 0.17 o/oo isohaline on 25 July 1987 to 39.25 at the 7.70 o/oo isohaline on 27 February 1987. When the peak phytoplankton biomass occurred in the very low salinity region, percent POC of total suspended matter was lower in the peak biomass zone than in the 2 o/oo isohaline region, while percent PON was higher in the peak biomass zone. Therefore, the ratio of POC to PON was significantly lower in the peak biomass zone than in the 2 o/oo isohaline region ($t = 3.130$, $0.02 < P < 0.05$) as shown in Table 4.

In summary, when peak phytoplankton biomass occurred in the very low salinity region, the ratio of POC to PON, the ratio of POC to chlorophyll *a*, and the percent dry weight of POC in total suspended matter were lower in the peak biomass zone than in the 2 o/oo isohaline region, while the ratio of chlorophyll *a* to phaeopigments, the ratio of PBS to POC, and the percent dry weight of PON, PBS and chlorophyll *a* in total suspended matter were higher in the peak biomass zone.

3-5 Nutrients

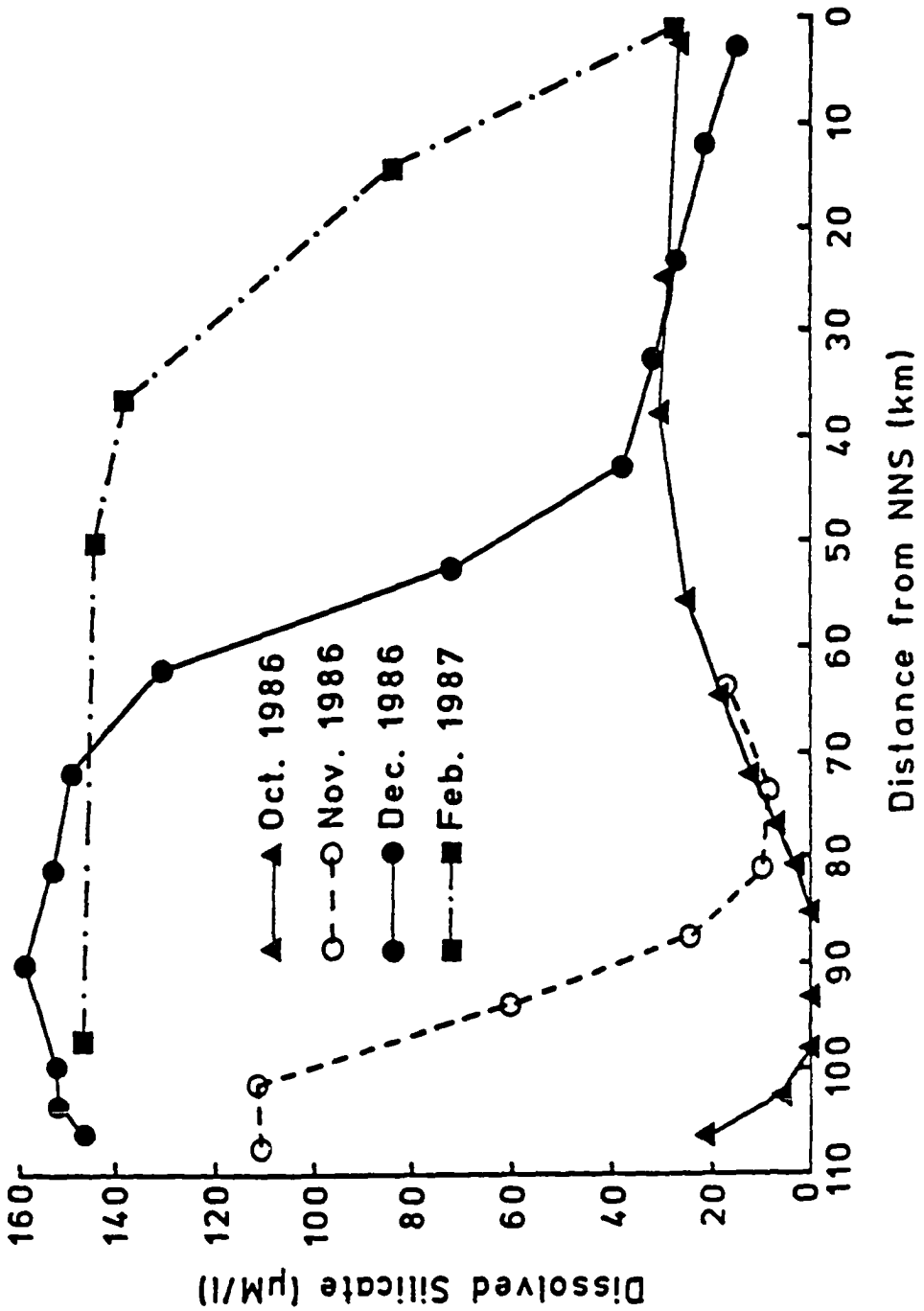
The results of the nutrient analyses are recorded graphically both in Appendix G as concentration (umole/L) and salinity versus the distance from a fixed station located off the Newport News Shipyard (NNS) and in Appendix H as concentration versus salinity for dissolved silicate, phosphate and nitrate plus nitrite (hereinafter referred to as nitrate).

Dissolved Silicate

The concentration of dissolved silicate ranged from undetectable levels on October 25, 1986 to 161.2 umole/L on January 21, 1987. Both maximum and minimum concentrations occurred in the very low salinity region (Appendix G and H). A composite silicate plot from October 1986 through February 1987 is shown in Figure 12. During months characterized by high river discharge (December 1986 through February 1987), dissolved silicate concentration was relatively high along the axis of estuary, exhibiting a somewhat conservative mixing. However, when discharge decreased (October and November 1986), there was almost complete removal of dissolved silicate in the very low salinity region, showing a non-conservative mixing.

In October 1986, the concentration was undetectable within the 0.17 - 0.84 o/oo mixing segment and in November 1986, minimum concentration occurred at the 0.87 o/oo isohaline (Appendix G and H). Removal rates in October and November, which were determined by the ratio of minimum

Figure 12. A composite silicate plot from the surface water along the estuary axis from October 1986 through February 1987.

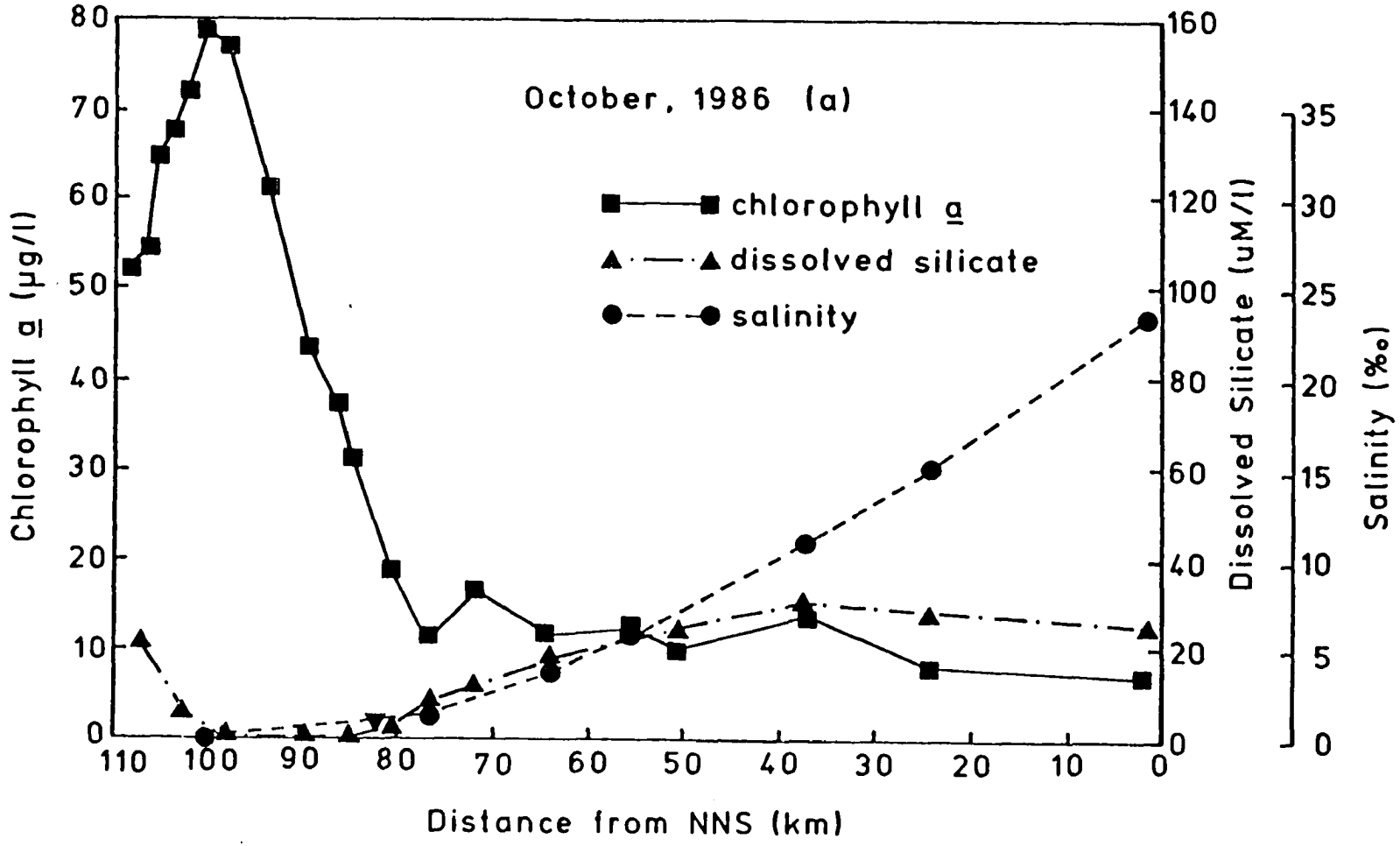


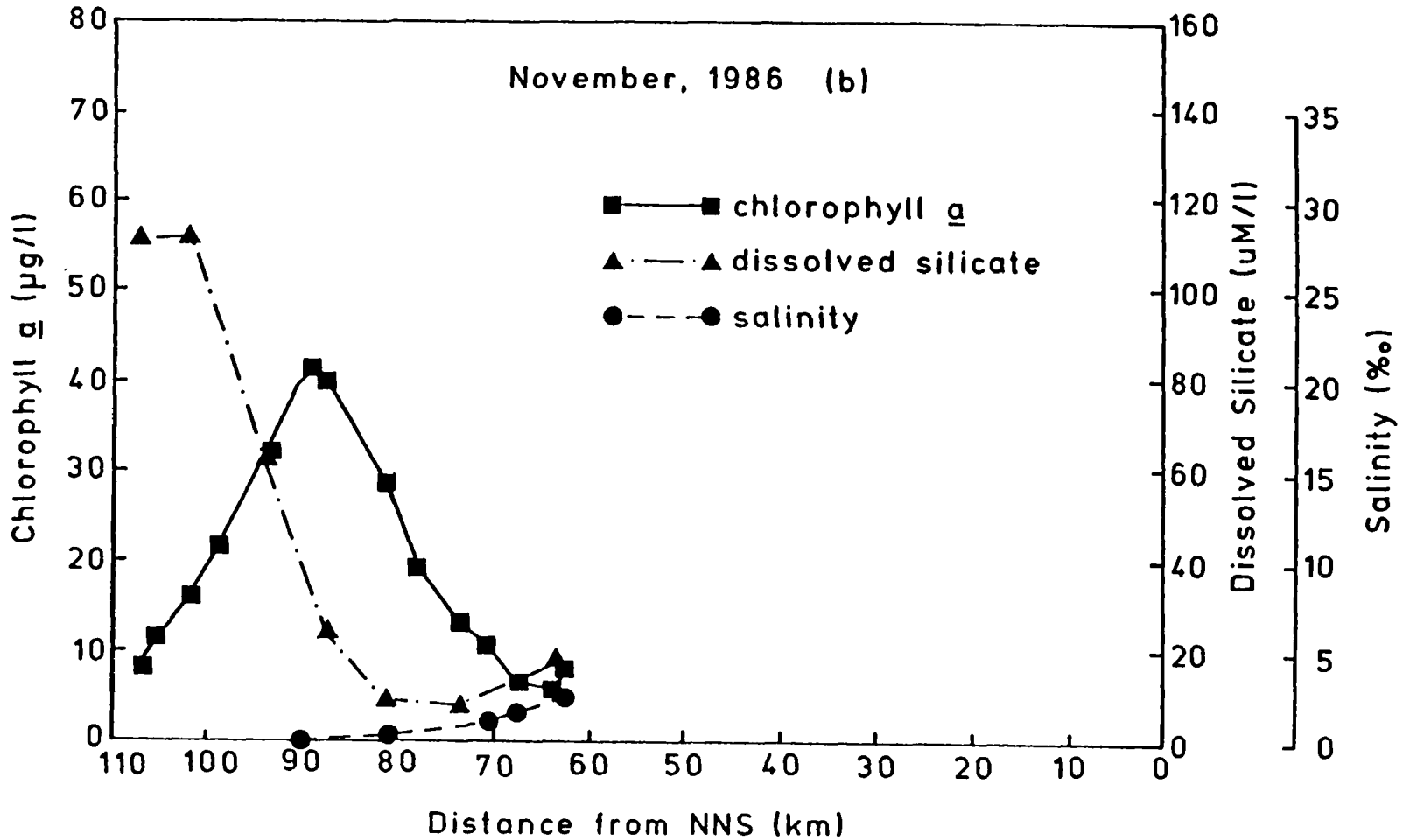
concentration in the very low salinity region to riverine concentration, were 100 and 92%, respectively.

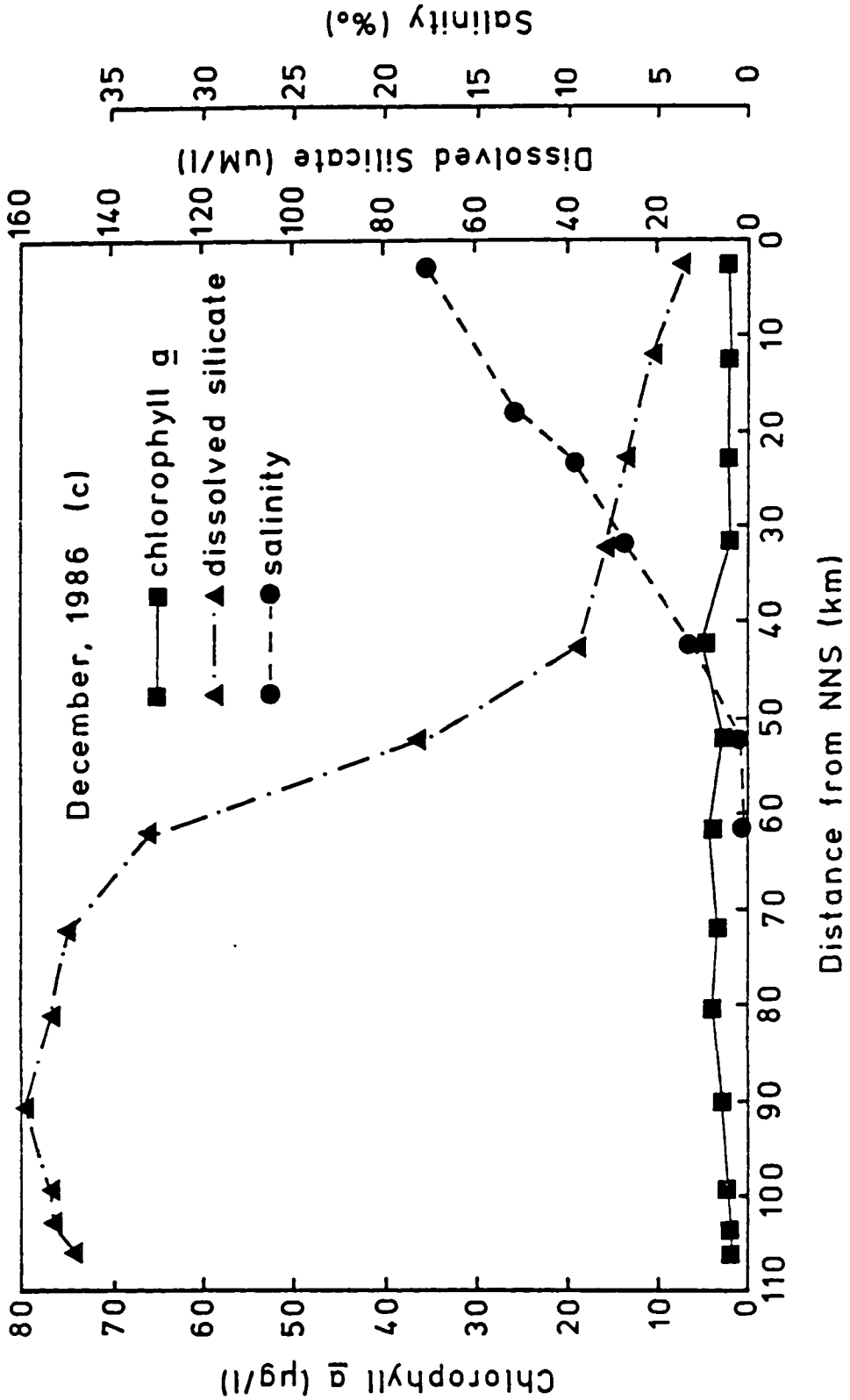
Another feature of dissolved silicate distribution during periods of low river discharge is an increase in concentration at mid-estuary. The increase in concentration in July and October 1986 occurred above the 10.45 o/oo and 11.11 o/oo isohaline, respectively (Appendix H). This is further downstream than the change at the 5 o/oo isohaline reported in the Rappahannock River estuary by Anderson (1986). The positive relationship with salinity indicates that there is a source within the estuary resupplying the dissolved silicate to the water column. During months characterized by high river discharge, high concentration in the freshwater zone (more than 140 umole/L) decreased steadily down-estuary until the lowest concentration (less than 27 umole/L) was achieved in the most saline water near the estuary mouth.

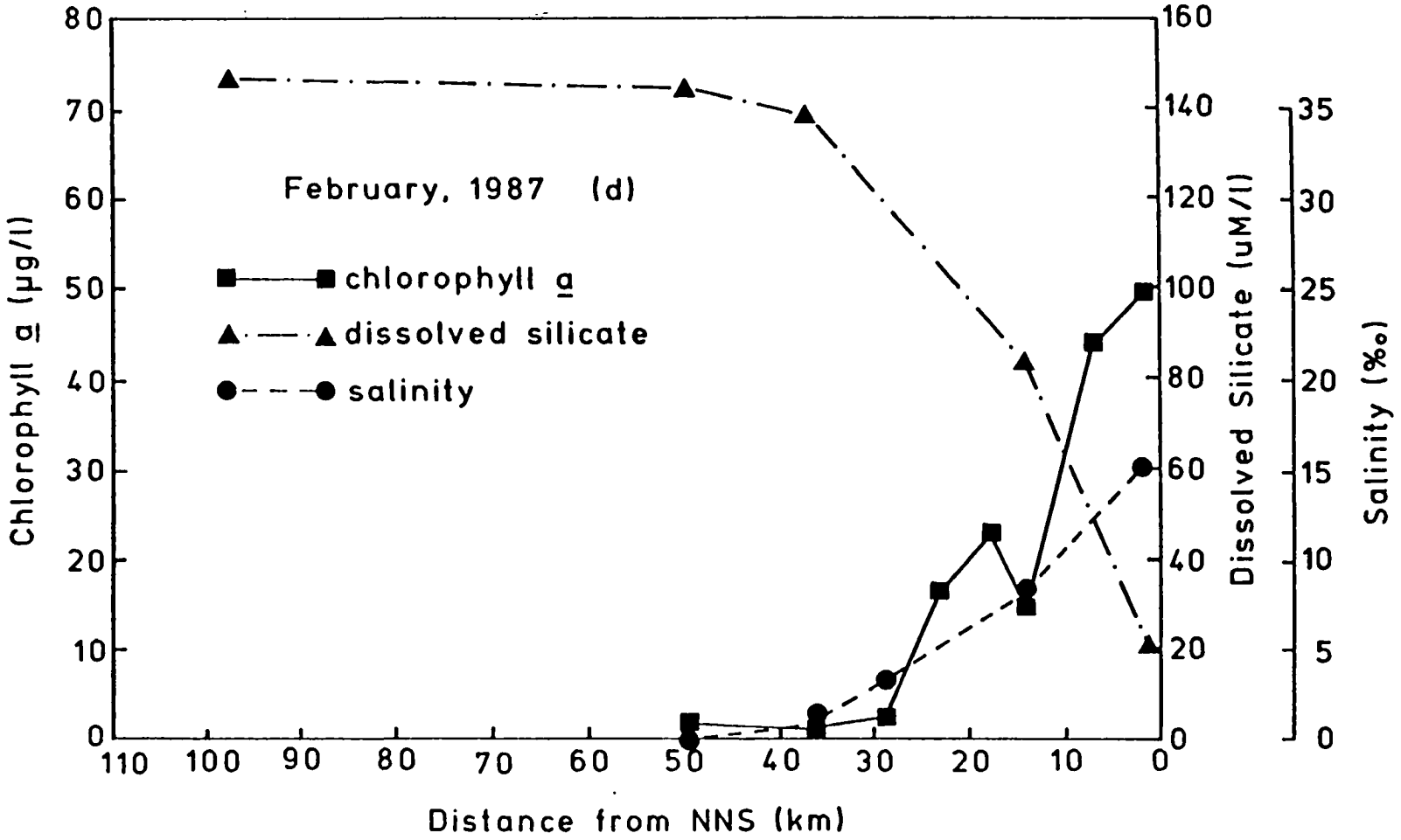
Figure 13 shows the longitudinal distribution patterns of the dissolved silicate, chlorophyll a, and salinity during October 1986 through February 1987. During periods of low river discharge (October and November 1986), there was a phytoplankton biomass peak in the very low salinity region and the zone of minimum dissolved silicate concentration corresponded to a maximum phytoplankton biomass, suggesting a cause and effect relationship, i.e. the diatoms are utilizing dissolved silicate in this region, and uptake by them exhausts the concentration below the detectable levels. During periods of high river discharge (December 1986 and February 1987) when peak biomass did not occurr, dissolved silicate concentration decreased steadily down estuary. Meanwhile, dissolved silicate concentration near the mouth of estuary ranged from 14.87 to 27.04 umole/L, varying little without regard

Figure 13. The longitudinal distribution of dissolved silicate, salinity and chlorophyll a from the surface water along the estuary axis: (a) October 1986, (b) November 1986, (c) December 1986, and (d) February 1987.









to the occurrence of phytoplankton biomass peak in the very low salinity region.

The concentrations of the dissolved silicate in both the surface and 1 m above the bottom in July 1986 and February 1987 are listed in Table 7. In July, which was characterized by the low river discharge, by maximum phytoplankton biomass and by dissolved silicate depletion in the very low salinity region, the concentration was higher in the bottom water than in the surface, especially within the 1.70 - 4.34 o/oo mixing segment. It implies that either resupplying from sediment occurs within this zone, or there is less removal at 1 meter above the bottom. However, in February, which was characterized by a high river discharge and conservative behavior of dissolved silicate, the concentration in the surface was always higher than that in the bottom.

Phosphate

Phosphate was generally present in concentrations of less than 9 umole/L (Appendix G). The distribution pattern along the axis of the estuary is almost identical with that of dissolved silicate. During the periods of low river discharge the concentration in the freshwater zone was high (up to 8.70 umole/L) and then decreased rapidly to undetectable levels in the very low salinity region where phytoplankton biomass peaked. Removal rate calculated in October and November 1986 was 100 and 90%, respectively. After removal within this zone, the concentration increased with salinity until the 15 - 20 o/oo isohaline. This is further downstream compared to the increase in dissolved silicate concentration which occurred until the 10 - 11 o/oo isohaline. During

Table 7. Dissolved silicate concentration from both the surface and 1 meter above the bottom on 25 July 1986 and on 27 February 1987 (D = distance from Newport News Shipyard, S = salinity, concentration unit = umole/L).

25 July 1986

D (km)	S (o/oo)	Surface	Bottom
0.9	23.00	27.04	24.85
30.4	10.45	50.82	51.76
54.6	4.34	39.38	45.77
69.0	1.70	25.27	29.05
95.2	0.20	2.22	2.87

27 February 1987

D (km)	S (o/oo)	Surface	Bottom
0.8	15.32	26.94	16.46
13.9	7.70	84.30	51.27
36.6	0.78	138.71	133.76
49.6	0.02	144.34	142.08
97.4	0	146.95	140.07

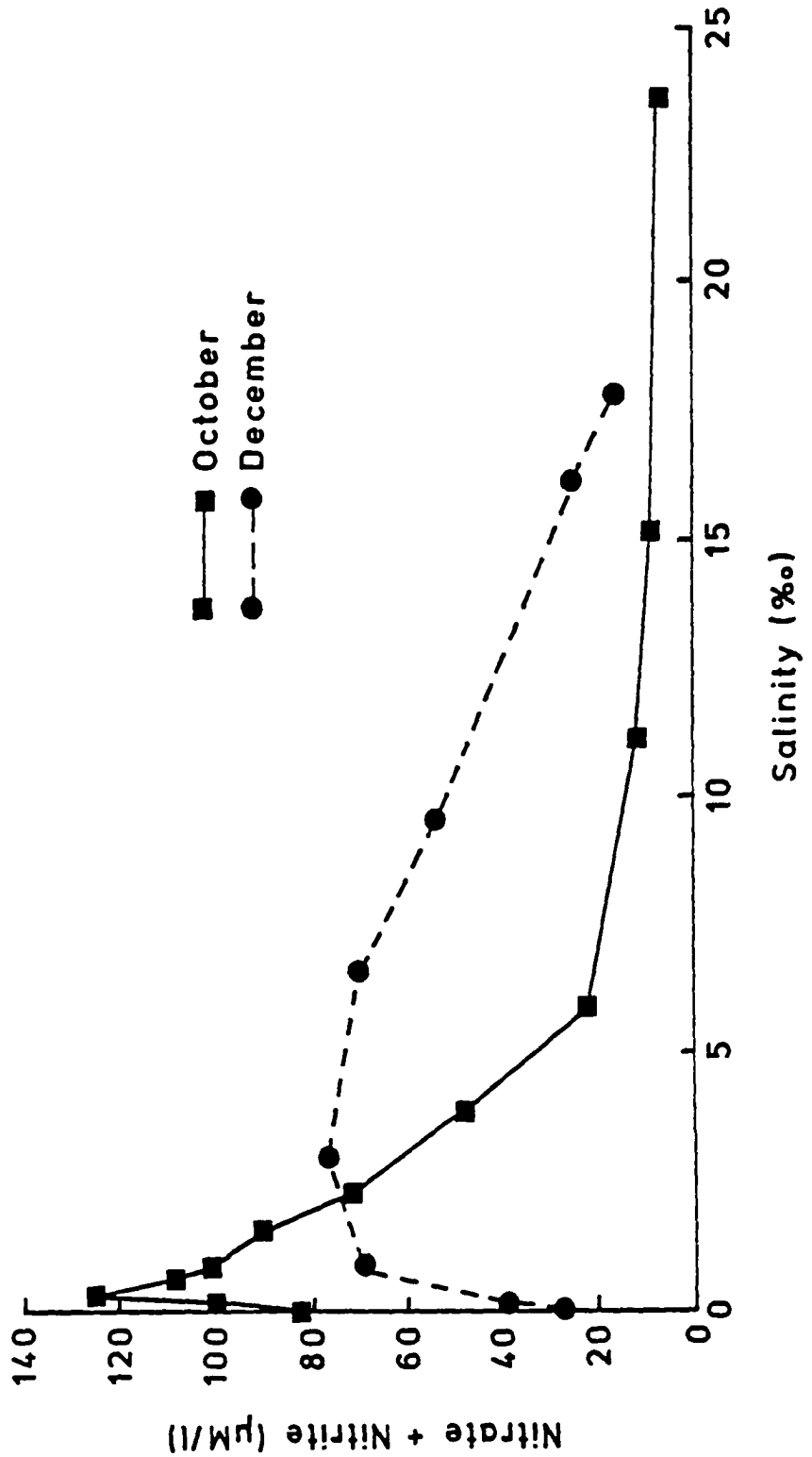
high river discharge, when the phytoplankton biomass was low within entire estuary, the distribution exhibited a somewhat conservative mixing. The high concentration in the freshwater zone decreased steadily down-estuary until the lowest concentration was achieved in the most saline water near mouth of the estuary.

Phosphate concentration near mouth of the estuary ranged from 0.66 to 1.67 umole/L, varying little with regard to the occurrence of the peak biomass in the very low salinity region.

Nitrate

Nitrate concentration ranged from undetectable levels in the 10.5 o/oo isohaline on 25 July 1986 to 136.2 umole/L in the 0.30 o/oo isohaline on 24 November 1986 (Appendix G). The nitrate distribution pattern along the axis of the main channel was different from that of dissolved silicate or phosphate (Fig. 14). The concentration in the freshwater was relatively low, usually less than 40 umole/L (the exception being October 1986, 83.9 umole/L) and it increased when freshwater mixed with seawater. During the summer and autumn months when the phytoplankton biomass peak occurred in the very low salinity region, nitrate concentration peaked in the approximately 0.3 o/oo isohaline, while it peaked in the 3.0 o/oo isohaline when the peak biomass disappeared during winter and spring. Maximum concentration in summer and autumn (up to 135 umole/L) was higher than that in winter and spring (up to 75 umole/L). After the maximum concentration of nitrate, during summer and autumn, there was a rapid decrease in concentration within the 0.3 - 6.0 o/oo mixing segment, and then nitrate concentration decreased

Figure 14. The longitudinal distribution of nitrate plus nitrite on 25 October and on 20 December 1986.



steadily. During winter and spring, the concentration decreased steadily downestuary; after the maximum concentration, until the lowest concentration was achieved at NNS. Consequently, nitrate mixed conservatively above the 6.0 o/oo isohaline without regard to the occurrence of phytoplankton biomass peak in the very low salinity region.

The nitrate concentration at NNS, during the time of the year when peak phytoplankton biomass occurred in the very low salinity region, ranged from 3.1 to 7.6 umole/L, while the concentration was higher during the months when the phytoplankton peak did not occur, ranging from 12.7 to 16.7 umole/L.

CHAPTER 4

DISCUSSION

4-1 Introduction

The data show that there is a phytoplankton biomass peak in the very low salinity region of the James River estuary during summer and autumn. The peak region has five to ten times greater biomass than adjacent waters further up and downstream (Appendix C). High phytoplankton biomass in the very low salinity region of the mid-Atlantic rivers are considered as natural phenomena. Brehmer (1972) and Anderson (1986) reported the high biomass within this zone of the York, the Rappahannock and the James River estuaries, Simpson et al. (1977) in the Hudson River estuary, D'Elia et al. (1983) in the Patuxent River estuary, Woodward (1983) and Bennett et al. (1986) in the Potomac River estuary, Filardo and Dunstan (1985) in the James River estuary, and Sharp et al. (1982) in the Delaware estuary.

Only a few studies have focused on the controlling processes responsible for the high phytoplankton biomass in the very low salinity region. Simpson (1977) and Bennett et al. (1986) assumed that the high biomass was due to the input of nutrients from anthropogenic sources in the upper estuary. The high phytoplankton biomass in the upper Hudson River estuary was attributed to nutrient enrichment from the New York City area which discharges runoff and waste water. In the Potomac River estuary, it was attributed to enrichment from the Washington, D.C. area.

In this study of the James River estuary, the location of nutrient

inputs does not seem to be responsible for causing the observed phytoplankton biomass peak in the very low salinity region. Maximum chlorophyll a (87.49 ug/L) in July 1986 which occurred 102.5 km upstream (located off the Hopewell city) decreased to very low biomass (16.06 ug/L) at the same position in November 1986 (Fig. 6), while the nutrient concentrations at this position still remained high (Appendix G). In November, the peak phytoplankton biomass occurred 13.4 km further downstream. However, the peak always occurred in the very low salinity region where salinity was less than 0.5 o/oo (Table 1). This supports the contention of Anderson (1986) who reported that the occurrence of the peak biomass in the very low salinity region of the tributaries of the Chesapeake Bay was not coupled with anthropogenic nutrient source.

From another viewpoint, nutrient limitation could not be responsible for the low phytoplankton biomass during the months of winter and spring when the peak biomass disappeared. In spite of the fact that dissolved silicate concentration was more than 140 umole/L, nitrate more than 30 umole/L, and phosphate between 6 to 7 umole/L in the very low salinity region, biomass was low, indicating that physical, not chemical, factors were controlling abundance within this zone.

The effect of the tidal state on the occurrence, the location and the magnitude of the phytoplankton biomass peak has not been investigated. There is evidence (Hass, 1977) that the James River estuary regularly oscillates between conditions of vertical homogeneity and stratification in conjunction with the monthly spring - neap tide. It was suggested that the increased tidal currents associated with the spring tide cause a shift from a stratified to a well-mixed water column and, conversely, decreased turbulent mixing during neap tides permitted

the reimposition of vertical stratification through the influx of higher salinity water along the bottom of the estuary. When the water column becomes destratified during the period of spring tide, the distribution of nutrients and oxygen also become homogeneous (Webb and D'Elia, 1980). Vertical mixing replenishes oxygen in the deep water, accelerating the input of regenerated benthic nutrients into the water column. The diurnal cycles of tide are known to affect the vertical distribution of total suspended matter with varying current speed (Nichols, 1972). In the North Sea, high levels of chlorophyll are deposited on the sediment surface during periods of slack current, thus providing a food source for benthic animals, while the deposited chlorophyll is resuspended during periods of flooding tide (Jenness and Duineveld, 1985).

Chlorophyll a data which were collected in the peak biomass zone in August 1987 showed that there is little variation in the phytoplankton biomass over the tidal cycle (Table 2). The distance between two locations of the peak during periods of flooding and spring tides in a day, which was measured on 25 October 1986, was approximately 3 km. The difference in chlorophyll a between phytoplankton biomass of the two peaks was less than 5 ug/L (Fig. 11). In addition, the monthly spring - neap tidal cycle did not affect the occurrence of the peak biomass. Monthly sampling was done at spring and neap tide in an alternating pattern from July 1986 through February 1987. The peak biomass occurred in July through November 1986 independent of the tidal state. From December 1986 through February 1987, the peak biomass did not occur again independent of the tidal state.

If it is true that phytoplankton biomass peak in the very low salinity region of the James River estuary occurs independent of the

location of nutrient inputs and tidal state, then what processes are responsible for causing the observed peak? The possible processes will be discussed in the following sections.

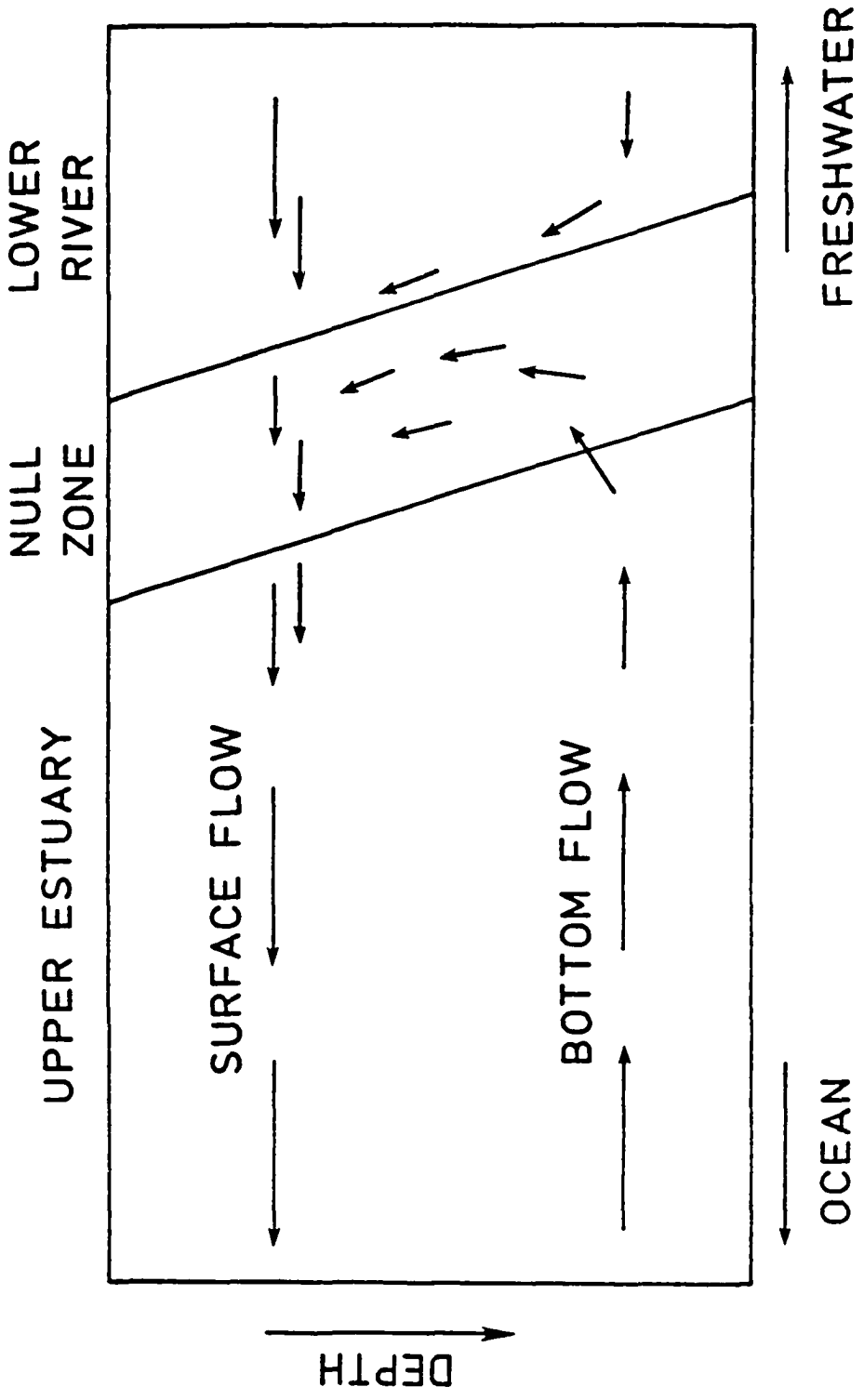
4-2 Hydrodynamic Trapping

The James River is an example of a partially-mixed estuary (Pritchard, 1952). Usually it is a moderately stratified estuary in which the dominant mixing agent is turbulence caused by tidal action. The salinity increases with depth and the salinity-depth curve has the general shape of an inverse tangent function. The partially-mixed estuary is often characterized by a non-tidal net circulation in which a surface layer of low-density water flows seaward over a landward flowing bottom layer of high-density water (Pritchard, 1967). A generalized diagram of the net circulation in the partially-mixed estuary is presented in Figure 15.

The distribution of suspended particles is influenced by such a non-tidal net circulation. Dense particles sink into the bottom current, which converges with river current near the landward extent of salt intrusion where bottom current is zero and upward vertical velocity is greatest (Hansen and Rattray, 1965;1967). Therefore, suspended particles accumulate to form a turbidity maximum near this convergence zone, or "null zone". Because particle concentration maxima result from a balance between sinking and vertical advection, only those particles having appropriate densities accumulate (Postma, 1967). Light particles are advected seaward in the surface layer and dense particles are not resuspended. Phytoplankton have a wide range of densities depending on their type and physiological state.

As river discharge controls the degree of mixing and thus regulates

Figure 15. A generalized diagram of the net circulation in a partially-mixed estuary (modified from Peterson et al., 1978).



the two-layer circulation, it also controls the trapping of particles to form a maxima. Highest suspended particle concentration has been encountered within a critical flow range, above which particles are advected seaward out of the maximum zone, and below which the landward and upward current are reduced so as not to trap and maintain particles in suspension (Nichols, 1972). The density - selective accumulation of suspended sediments by estuarine circulation is documented in the northern Chesapeake Bay (Schubel, 1969), the Rappahannock River estuary (Nichols and Poor, 1967), the James River estuary (Nichols, 1972) and the northern San Francisco Bay (Conomos and Peterson, 1977).

The phytoplankton biomass peak in the very low salinity region of the James River estuary could be caused by the same mechanism involved in the formation of the turbidity maximum in partially-mixed estuaries. The trapping model nicely explained the phytoplankton dynamics of the partially-mixed northern San Francisco Bay. With a series of mathematical simulations verified by field studies, Peterson et al. (1978) demonstrated that freshwater discharge, as it influences the trapping of particulates to form the turbidity maximum, also regulates the phytoplankton biomass in the low salinity portion of the estuary.

Ball and Arthur (1981) measured the settling velocity of natural phytoplankton assemblages (dominated by the diatoms, Thalassiosira eccentrica and Skeletonema costatum) in the northern San Francisco Bay by following the time - course of chlorophyll settling in a 25 cm tube. In the area around the turbidity maximum, calculated sinking rates ranged between 1.5 - 6 m per day (averaged about 3 m per day) and the high sinking rates were attributed to the secretions by the dominant species which bind particulate materials to the cells. The sinking rates of this

magnitude are close to calculated net upward vertical water velocity (3.4 m per day) in the null zone of the northern San Francisco Bay during normal summer river discharge (O'Connor and Lung, 1981).

In the James River estuary, the net upward vertical water velocity at the 12.5 o/oo isohaline during normal summer river discharge was calculated as 0.9 m per day (Pritchard, 1967). The velocity in the null zone will be increased because the upward velocity within this zone is known to be greatest (Hansen and Rattray, 1965;1967). The net upward vertical velocuty in the null zone during normal winter river discharge (251 m^3sec^{-1}) was calculated as 1.8 m per day (O'Connor and Lung, 1981). When river discharge decreases, the vertical velocity will be decreased (Schubel, 1969; Festa and Hansen, 1978; Peterson and Festa, 1984). Therefore, during summer and fall (river discharge was between 28.3 and 111.6 m^3sec^{-1}) when peak phytoplankton biomass occurred in the very low salinity region in this study, the net upward vertical water velocity was calculated to be between 0.9 and 1.8 m per day. Smayda and Boleyn (1966) measured phytoplankton sinking rates in culture. The mean sinking rate of a diatom, Skeletonema costatum ranged from 0.30 to 1.35 m per day and the rate of another diatom, Rhizosolenia setigera, ranged from 0.16 to 1.77 m per day. In this study, a dominant species in the peak biomass zone was a diatom, Melosira sp. Due to heavily silicified frustules of this species (Anderson, 1986), the sinking rate is probably close to the maximum phytoplankton sinking rates reported by Smayda and Boleyn (1966). In Appendix I, the sinking rate of this species was calculated by using a Komar's equation (Komar, 1980) for a cylindrical-shape particle. Rates ranged from 0.9 to 1.6 m per day at 5°C and 25°C, respectively. These temperatures represent the seasonal range measured in the study area

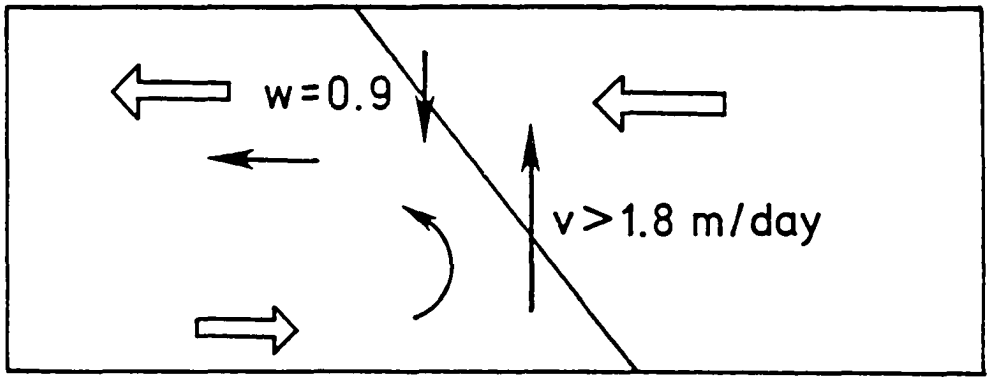
(Appendix A). Figure 16 shows the sinking rates of this species and net upward vertical water velocity in the null zone during periods of both high-river discharge (winter) and low-river discharge (summer). Significantly, during periods of low river discharge, the sinking rates of this species closely balance the net upward vertical water velocity in the null zone of the James River estuary.

Cloern et al. (1983) demonstrated that neritic diatoms are selectively trapped in the turbidity maximum zone of the upper San Francisco Bay. They measured the percent netplankton biomass (retained by 22 um screen) of the total. The netplankton comprised more than 80%, suggesting that lighter forms of phytoplankton, such as flagellates, are advected seaward out of the turbidity maximum zone.

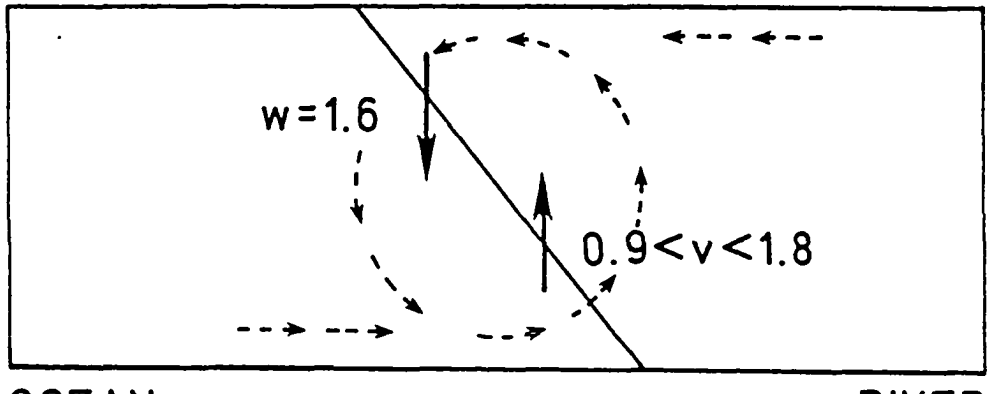
In the James River estuary, the percent netplankton biomass (retained by 28 um screen) in the very low salinity region was significantly higher than the percent at the 2 o/oo isohaline during the months when the phytoplankton biomass peak occurred (Fig. 10). This suggests that diatoms are selectively trapped in this zone, because the size of diatoms is usually larger than 25 um. However, the netplankton chlorophyll _a_ was usually less than 50% of the total biomass, while more than 80% was reported in the upper San Francisco Bay (Cloern et al., 1983). Netplankton biomass in the James River estuary was determined by subtracting the nanoplankton biomass from the unfractioned biomass. This is probably an underestimation because the nanoplankton biomass was not corrected for the soluble fractions (passing the glass fiber filter) which originate from other than phytoplankton such as broken cells. However, the percentage of soluble chlorophyll _a_ is known to range only from 0 to 6% with an average 2% in the San Francisco Bay (Alpine and

Figure 16. Sinking rates (w) of a diatom, Melosira sp, and net upward vertical water velocity (v; calculated from O'Connor and Lung, 1981 and Pritchard, 1967) in the 'null' zone during periods of (a) high river discharge (winter) and (b) low river discharge (summer).

(a) High River Discharge (Winter)



(b) Low River Discharge (Summer)



Cloern, 1985). Thus, the percent netplankton biomass in the James River estuary is still relatively low compared to the biomass in the San Francisco Bay, even when soluble chlorophyll a is considered. Aggregation of other smaller phytoplankton with clay particles (Avnimelech, 1982) or shrinkage of freshwater phytoplankton due to osmotic stress (Guillard, 1962) may enhance their sinking rates, and thus optimize the likelihood of retention by estuarine circulation in the turbidity maximum zone.

In addition to netplankton biomass, the distribution pattern of dissolved silicate along the axis of an estuary can be an important parameter for investigating the diatom distribution. From this study, most of the inflowing riverine supply of dissolved silicate was removed in the very low salinity region when the peak biomass occurred within this zone (Fig. 13), suggesting that diatoms are selectively trapped within this zone.

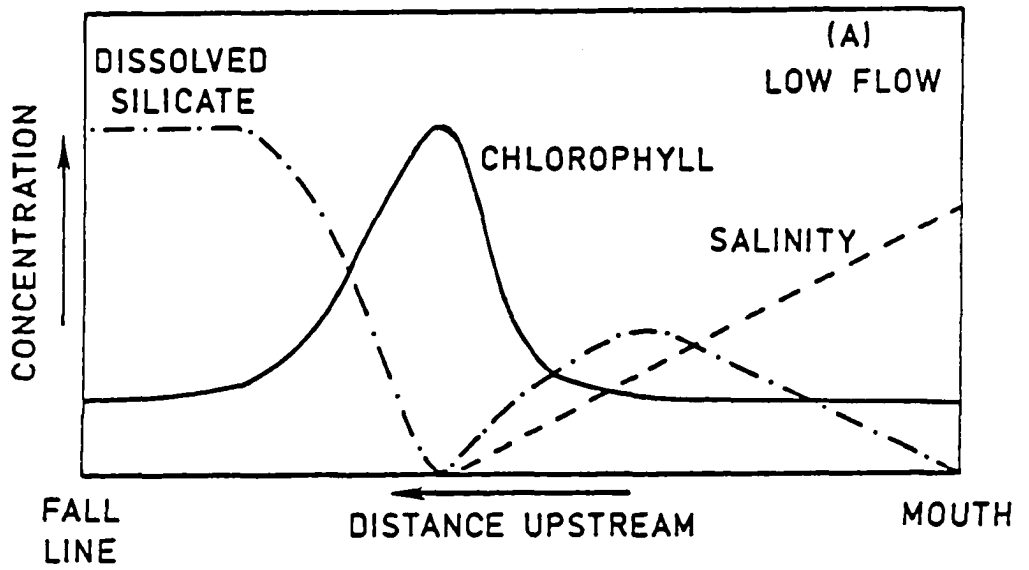
The most significant allochthonous source of dissolved silicate in an estuary is riverine input of silicate produced both from weathering and dissolution of crustal mineral crystals and from the decay of biological material such as terrestrial plants that contain silica (Silverman, 1979). Municipal wastewater contains low amounts of silicate (Officer and Ryther, 1980), and thus contributes little to the estuary. Although non-biological removal of dissolved silicate was reported in the Conway River estuary (Liss and Spencer, 1970) and in the Tamar estuary (Morris et al., 1981), most removal of dissolved silicate is known to occur by diatom uptake (Peterson et al., 1978; D'Elia et al., 1983; Yamada and D'Elia, 1984). Diatoms take up the dissolved silicate to build tests or frustules (Conway et al., 1977).

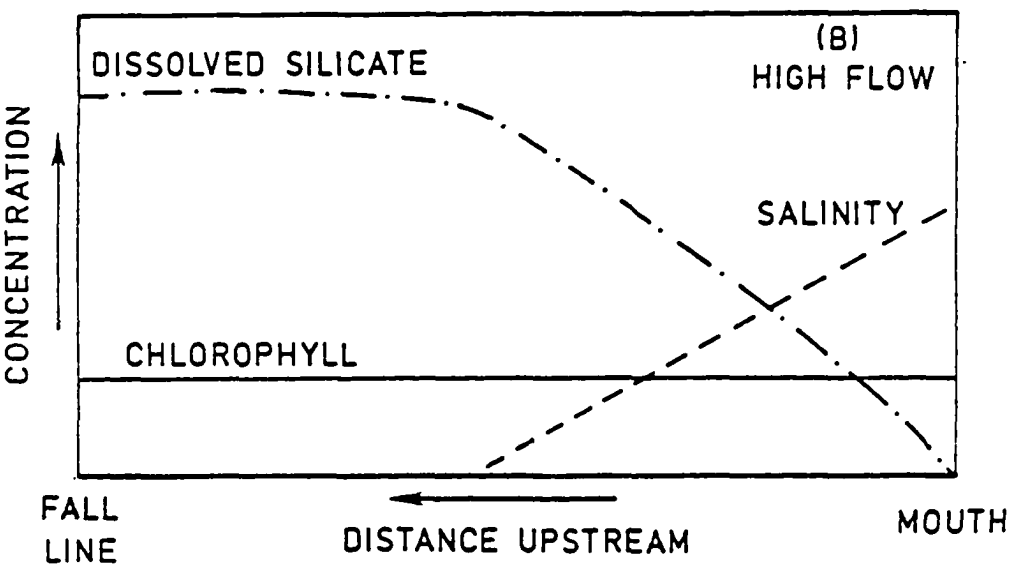
According to the time series of monthly surveys (Fig. 12), during winter and spring (periods of high river discharge), dissolved silicate distributions appear conservative. However, the characteristic non-conservative pattern appears and prevails during summer and fall (periods of low river discharge). Figure 13 shows that peak phytoplankton biomass clearly corresponds to the minimum dissolved silicate concentration. Both maximum phytoplankton biomass and the dissolved silicate minimum occurred in the very low salinity region.

A similar distribution pattern of dissolved silicate and phytoplankton biomass has been reported in many estuaries. Simpson et al. (1977) reported dissolved silicate depletion corresponding to high phytoplankton biomass in the very low salinity region of the Hudson River estuary. Similar results were reported by D'Elia et al. (1983) in the Patuxent River estuary and Anderson (1986) in the tributaries of the Chesapeake Bay. A generalized model of the distribution of salinity, chlorophyll a and dissolved silicate for the periods of high and low river discharge is presented in Figure 17. During periods of low river discharge, the exhaustion of dissolved silicate in the very low salinity region is due to the high diatom biomass trapped within this zone. During periods of high river discharge, the peak biomass disappears and dissolved silicate distribution becomes conservative.

The dry weight ratio of particulate biogenic silica (PBS) to particulate organic carbon (POC) also shows that diatoms are selectively trapped in the very low salinity region. When peak phytoplankton biomass occurred in the very low salinity region, the ratios in the peak biomass zone were 0.19 and 0.18 in July and August 1987, respectively (Table 3). These values are comparable to the ratio of 0.24 - 0.26 reported by

Figure 17. A generalized model of the distribution of salinity, chlorophyll and dissolved silicate (a) during periods of low river discharge (b) during periods of high river discharge (modified from Anderson, 1986).





Paasche (1980) for healthy growing culture of a diatom, Skeletonema costatum at 18°C and the ratio of 0.2 - 0.3 reported by Paasche and Ostergren (1980) for the spring diatom bloom in the Oslofjord. Thus, ratios in this study indicate that diatoms significantly contribute to the POC in the peak biomass zone. Relatively low ratios in the very low salinity region of the James River estuary are probably due to non-living detritus and other phytoplankton species which also comprise POC in the peak biomass zone. In February 1987, near the mouth of the estuary, where the spring diatom bloom occurred and the magnitude of the turbidity was low, the rate was 0.21 (Table 3) which agrees well with the ratios reported by Paasche and Ostergren (1980). The ratio in the 2 o/oo isohaline region averaged 0.01 during periods that peak biomass occurred (Table 4). This suggests that diatom biomass decreases rapidly within a narrow range of salinity.

The ratio of POC to chlorophyll a by dry weight is known to vary with species composition of the phytoplankton assemblage (Steele and Baird, 1962; Lorenzen, 1968; Eppley et al., 1977). The ratios for the diatom bloom were reported as 42 and 40.5 in the southern California bight (Eppley et al., 1977) and in the Peruvian upwelling area (Lorenzen, 1968), respectively. The ratio was between 78 and 209 for the dinoflagellate bloom in the southern California bight. In the James River estuary, the ratio ranged from 51.2 to 67.5 (averaged 62.0) in the peak biomass zone (Appendix D), suggesting that diatoms significantly contribute to POC in the peak biomass zone. Relatively high values in this sudy are probably due to non-living detritus and other phytoplankton species in the peak biomass zone. In February 1987, during the spring diatom bloom at the mouth of the estuary, the ratio was 48.9 (Appendix D)

which agrees well with the ratios reported by Eppley et al. (1977) and Lorenzen (1968) for diatom blooms. The ratio in the 2 o/oo isohaline region averaged 146.1 during periods that peak biomass occurred (Table 4), indicating low diatom abundance in this zone.

A sample selected from the peak biomass zone in June 1987 was used to make a qualitative assesment, using a microscope, as to whether diatoms were dominant or not. Dominant species in the peak biomass zone were freshwater forms of diatoms having heavily silicified frustules. The species were Melosira sp, Cyclotella sp, Synedra sp, Cocconeis sp, Gyrosigma sp, Navicula sp and Surirella sp.

Consequently, the settling velocity of dominant phytoplankton species, the percent netplankton biomass, the dissolved silicate distribution, the ratio of PBS to POC, and the ratio of POC to chlorophyll a in the very low salinity region all indicate that diatoms are selectively trapped within the turbidity maximum zone during periods of low river discharge (summer and fall).

While it is hypothesized that the observed phytoplankton biomass peak in the very low salinity region of the James River estuary is caused by the same trapping mechanism involved in the formation of the turbidity maximum in partially mixed estuaries, the higher phytoplankton biomass did not seasonally correspond to the greater magnitude of the turbidity maximum.

The magnitude of the turbidity maximum in the James River estuary was proportional to the river discharge as shown in Figure 3. As river discharge increased, the turbidity maximum zone moved in the seaward direction and the magnitude of the turbidity maximum increased. Nichols (1972) also indicated that the turbidity maximum in the James River

estuary is most pronounced in spring when river flow is high. Unlike the magnitude of the turbidity, phytoplankton biomass in the very low salinity region of the James River estuary varied inversely with river discharge (Fig. 7). Surface phytoplankton chlorophyll a within this zone typically increased when mean monthly discharge fell below about 120 m^3sec^{-1} in the spring, peaked in summer, declined in fall, and reached a minimum during peak winter discharge. Similar variations in phytoplankton abundance and river discharge in the very low salinity region have been noted in the Potomac River estuary by Sze (1981) and Bennett et al. (1986), in the San Francisco Bay by Peterson et al. (1978) and Cloern et al. (1983), and in the James River estuary by Filardo and Dunstan (1985).

As river discharge increases, the net non-tidal circulation in the San Francisco Bay is known to become stronger and the net upward vertical velocity to become larger (Festa and Hansen, 1978; Peterson and Festa, 1984). Therefore, higher settling velocities are required to develop a turbidity maximum. Schubel (1969) showed that the mean diameter of particles in the turbidity maximum of the Chesapeake Bay is larger in winter than in summer. Meanwhile, the sinking rate of a diatom during winter (Fig. 16) decreased due to the increased coefficient of dynamic viscosity at low temperature (Appendix I). Therefore, diatoms are probably not trapped in the turbidity maximum zone of the James River estuary during winter and spring due to both decreased sinking rate of phytoplankton and increased net non-tidal circulation.

The reverse relationship of phytoplankton biomass with river discharge (Fig. 7) indicates the hydrodynamic control over phytoplankton biomass in the very low salinity region. Water residence time, the

average time required for water to enter and leave the estuary, is influenced by both advective and diffusive processes. River discharge and density currents control advective processes, while wind and tidal mixing control diffusive processes. In general, river currents decrease in the seaward direction with increasing cross-channel areas, whereas landward flowing density currents ultimately weaken to equal the opposing river current (Peterson et al., 1978). The net effect of these processes may produce a longitudinal variation in the advective and diffusive replacement time of a substance. As river discharge increases, the null zone shifts seaward, the residence time decreases, and longitudinal variations in advective water replacement time may become relatively small. Decreased residence time during periods of high river discharge results in a low phytoplankton biomass in the very low salinity region of the James River estuary.

Though there was an inverse relationship between maximum biomass and river discharge in each year, the biomass in summer was higher in 1987 than in 1986 with almost identical river discharge (Fig. 8). A similar phenomenon was observed in the Potomac River estuary by Bennett et al. (1986), who reported that high-river discharge in spring was associated with high biomass in the following summer. It was suggested that spring floods deliver large loads of particulate nitrogen and phosphate to the tidal river, and these particulate matter is mineralized by bacteria to inorganic nitrogen and phosphate, released to the water column and made available for phytoplankton use. However, in the James River estuary, nutrients limitation was not responsible for the lower biomass in summer 1986. Other factors such as light or temperature may be involved in causing the higher biomass in summer 1987.

There were some differences between the turbidity maximum zone and the location of maximum phytoplankton biomass observed in the James River estuary (Fig. 18). The peak biomass in the San Francisco Bay was observed within the 3 - 5 o/oo isohaline and the distribution coincided with that of the turbidity maximum (Conomos and Peterson, 1977). In the James River estuary, the turbidity maximum occurs within the 0.5 - 2 o/oo isohaline (Feuillet and Fleischer, 1980), while the phytoplankton peaks observed in this study always occurred in the very low salinity region (less than 0.5 o/oo). Relative percentage transmissions measured during surveys of the James River estuary show that the turbidity maximum encompasses a much broader area, extending downstream to approximately 8 o/oo isohaline as shown in Appendix B. If hydrodynamic trapping is responsible for peak phytoplankton biomass in the James River estuary, then an unanswered question is why does phytoplankton biomass also not accumulate further downstream, a region where other inorganic suspended particles are still accumulating?

The distribution and abundance of phytoplankton in an estuary are determined by the biological processes in addition to the transport mechanism that affects suspended sediments. In addition to behaving like inorganic particles, phytoplankton cells also grow, divide, decompose or are consumed. Figure 19 shows that peak phytoplankton biomass in the very low salinity region decreases very rapidly before the approximately 1.5 o/oo isohaline. The chemical compositions of total suspended matter also show rapid decrease in phytoplankton biomass within a narrow range of salinity. Both decreased ratio of particulate biogenic silica to POC and increased ratio of POC to chlorophyll _a_ (Table 4) in the 2 o/oo isohaline region suggest that high diatom biomass in the peak biomass

Figure 18. Surface phytoplankton biomass and total suspended matter from the surface water along the estuary axis on 15 July 1987.

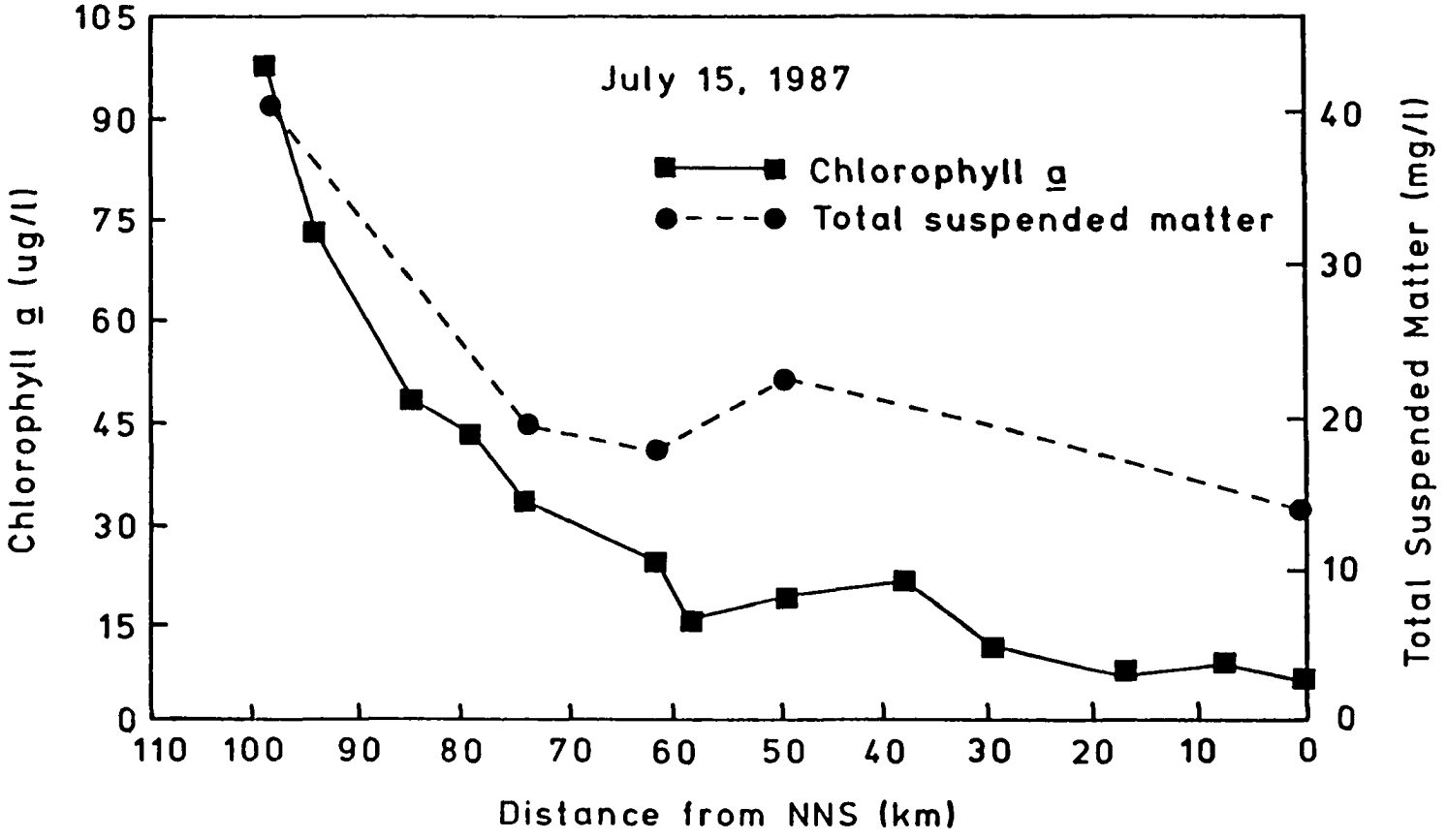
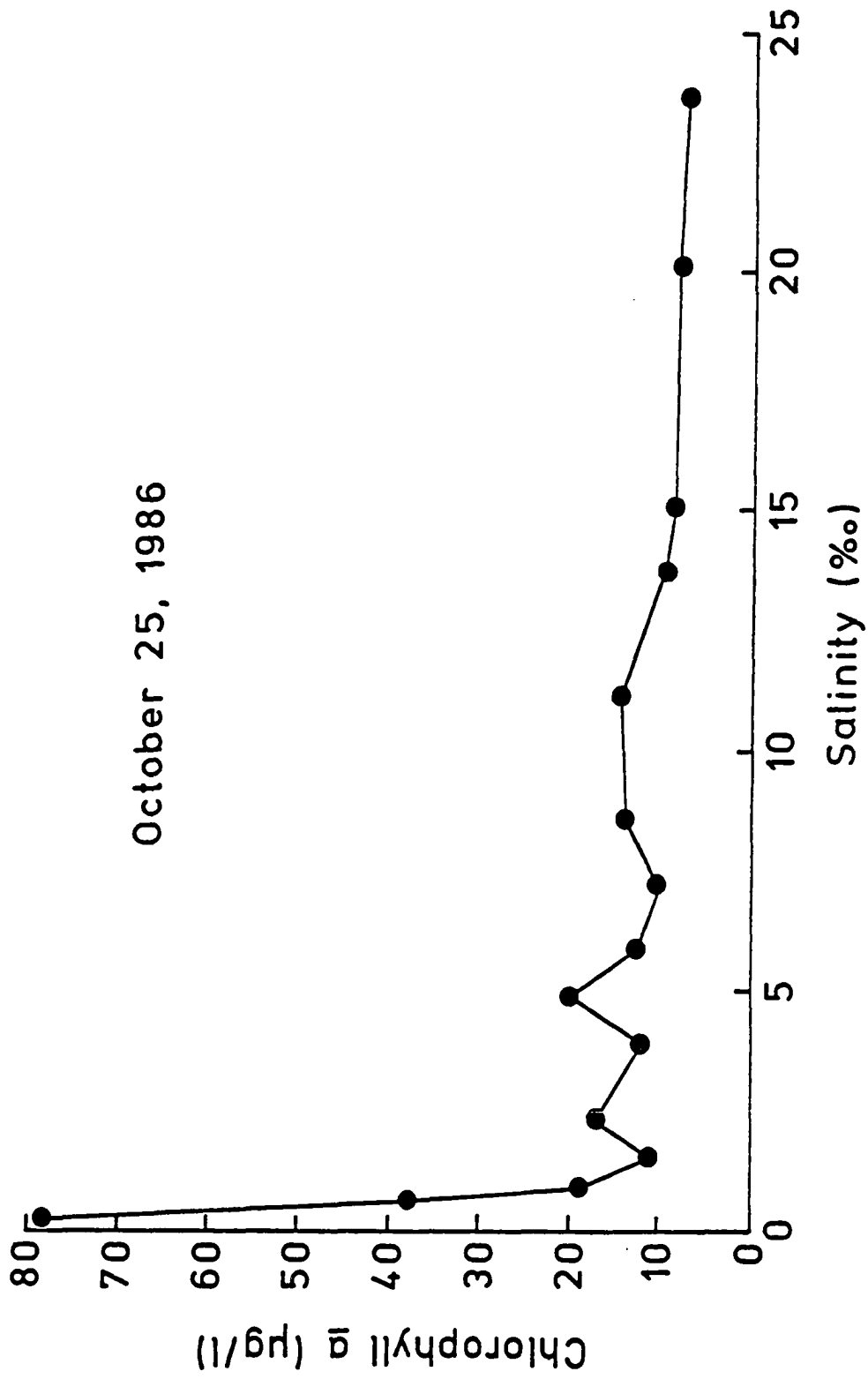


Figure 19. Surface phytoplankton biomass versus salinity from the surface water along the estuary axis in October 1986.



zone (less than 0.5 o/oo) decreases rapidly (Lorenzen, 1968; Eppley et al., 1977; Paasche, 1980; Paasche and Ostergren, 1980). Percent dry weights of chlorophyll a and particulate biogenic silica in total suspended matter decreased considerably within a narrow range of salinity (Table 5).

The physiological state of phytoplankton (degree of health or senescence) in the peak biomass zone was different from that in the 2 o/oo isohaline region. The relatively low ratios of POC to PON and relatively high ratios of chlorophyll a to phaeopigments in the peak biomass zone compared to the ratios in the 2 o/oo isohaline region (Table 4) indicate that phytoplankton in the peak biomass zone are in better physiological condition. The atomic ratio of POC to PON, and the ratio of chlorophyll a to phaeopigments are indicative of phytoplankton health. The ratio of POC to PON for healthy growing phytoplankton is known to be close to 6.6 (the Redfield ratio, Redfield, 1958), while the ratio increase for the phytoplankton growing in poor condition. The ratio of fluorescence values before acidification (Rb) to fluorescence after acidification (Ra) in pure chlorophyll a is known to be 2.2 (Holm-Hansen et al., 1965). The ratio is usually greater than 1.7 for healthy growing phytoplankton, while extracts of marine muds and crustaceans yield the values of around 1.0 (Yentsch and Menzel, 1963). Phytoplankton with a lower rates of Rb to Ra have more decomposition products of chloroplastic pigments (Yentsch and Menzel, 1963). Therefore, the lower ratios of POC to PON will be related to the higher ratios of Rb to Ra. As shown in Figure 20, the ratio of Rb to Ra is inversely related to the ratio of POC to PON ($n = 23$, $r = -0.6600$). As the ratio of POC to PON increases, the ratio of Rb to Ra decreases. Increased ratios of POC to PON in the 2

Figure 20. The relationship between the ratio of fluorescence values before acidification to fluorescence after acidification of extracts (Rb/Ra) and the ratio of particulate organic carbon to nitrogen (POC/PON).

o/oo isohaline region compared to the ratio in the peak biomass zone indicate that decomposition of organic nitrogen in phyto-detritus is faster than organic carbon.

Several hypotheses have been suggested to account for the rapid decrease of high phytoplankton biomass in the very low salinity region. These include: (1) an increase in suspended sediment attributable to the turbidity maximum, which by decreasing light penetration causes a decrease in biomass (Sharp et al., 1982; Pennock, 1983); (2) an increase in flocculation resulting in an increased sedimentation of phytoplankton together with sediments (Avnimelech et al., 1982; Edzwald et al., 1974); and, (3) a mass mortality resulting from the osmotic stress placed on freshwater halophobic phytoplankton (Morris et al., 1978; 1982; Filardo and Dunstan, 1985).

The initial decrease in phytoplankton biomass in the Delaware estuary was attributed to an increase in suspended sediment in the low salinity region (Sharp et al., 1982; Pennock, 1983). Undoubtedly, the decreasing light penetration associated with the turbidity maximum restricts the amounts of photosynthesis which can occur by limiting the photic zone. Peterson and Festa (1984) attributed the decline of phytoplankton biomass in the northern San Francisco Bay during periods of high river discharge to the light limitation caused by a high concentration of suspended sediment. However, it is questionable whether or not the turbidity maximum is responsible for the initial decrease in biomass. High phytoplankton biomass occurred in July 1986 and August 1987 at Hopewell city (Fig. 6), where the turbidity was relatively strong over the duration of the study (Fig. 3). The same physical processes which are responsible for the formation of the turbidity maximum also

serve to readvect phytoplankton from deeper waters into the euphotic zone (Arthur and Ball, 1981; Cloern et al., 1983; Anderson, 1986).

Mutual flocculation of algae and colloidal particles may cause the initial decrease in biomass through increased settling. Clay minerals, a large fraction of colloidal particles, carry an electrical charge, which is usually negative in natural waters. In freshwaters, repulsive forces between the negatively charged particles dominate, resulting in a stable suspension. In saline waters, net interparticle forces become attractive and particles that collide tend to cling to each other to form flocs (Edzwald et al., 1974). Avnimelech et al. (1982) presented evidence that Anabaena sp, Chlamydomonas sp and Chlorella sp begin to aggregate with clay particles at salinities greater than 1.5 o/oo. It is doubtful that flocculation may contribute heavily to the initial decrease in biomass within the 0 - 2 o/oo mixing segment of the James River estuary. Moreover, the enhanced sinking rates of phytoplankton with attaching grains may closely balance upward advective flow in the null zone, and thus the phytoplankton could comprise the peak biomass.

Evidence from the Tamar estuary (Morris et al., 1978; 1982) and the James River estuary (Filardo and Dunstan, 1985), which suggests that a mass mortality of freshwater halophobic phytoplankton occurs in a narrow range of salinity, is the most promising mechanism responsible for the initial decline of biomass in the very low salinity region. Morris et al. (1978) reported that the mass mortality results in a continuous plasmolytic release of easily degradable dissolved organic material. Anderson (1986) calculated cell quotas in the Rappahannock River estuary by dividing the biogenic silica concentration measured for a sample by the density of diatoms determined by counting. The abnormally high value

in the low salinity portion (within 0 - 5 o/oo mixing segment) indicates that diatomaceous silica is present in the water column in a form which could not be recognized under the microscope as whole cells. The fragmented diatom frustules in the water column are probably a result of mass mortality of freshwater diatoms that were incapable of withstanding the sudden osmotic stress resulting from being advected into the estuary.

Many studies demonstrate that euryhaline microalgae can tolerate wide ranges of salinities in laboratory experiments. For example, Thalassiosira sp can tolerate from 2.5 to 35 o/oo (Mclachlan, 1961), Olithodiscus sp from 3 to 33 o/oo (Tomas, 1978), Cryptomonas sp from 3.5 to 52 o/oo (Liu and Hellebust, 1976) and Nannochloris sp from 3 to 300% artificial seawater (Brown, 1982). It seems somewhat of a paradox that many phytoplankton species can grow within a relatively wide range of salinity in culture, while they have a very narrow range of salinity for survival in nature. However, laboratory studies which employ batch culture and single salinity change may not be acceptable analogs of the natural system when considering osmotic stress. Filardo and Dunstan (1985) indicated that the absolute percentage of freshwater phytoplankton that survive in more saline water becomes small with decreasing river discharge, because the time it is exposed to a repeated osmotic stress becomes long. It was suggested that the rate of change of salinity, the time associated with the osmotic stress, and/or the exposure to a repeated osmotic stress are more significant factors in determining a cell's survival than the magnitude of the salinity change.

4-3 Nutrients

The occurrence of the peak phytoplankton biomass and selective trapping of diatoms in the very low salinity region during summer and fall, and disappearance of the peak biomass during winter and spring affect the distribution patterns of nutrients along the estuary axis.

Dissolved Silicate

When the peak biomass did not occur, high concentration of dissolved silicate in the freshwater zone decreased steadily down-estuary until the lowest concentration was achieved in the most saline water near the estuary mouth (Fig. 13). However, during the periods that the peak biomass occurred in the very low salinity region, there was almost complete removal of dissolved silicate within this zone and then increase in concentration with salinity in the mesohaline region (within the 0.5 - 10 o/oo mixing segments), indicating that there is an input source within the estuary. A similar distribution pattern of dissolved silicate in the mesohaline region was also observed in other estuaries. D'Elia et al. (1983) reported increased concentrations of dissolved silicate within the 2 - 10 o/oo mixing segment of the Patuxent River during summer. Anderson (1986) observed that the increase in the concentration in the Rappahannock River occurs above the 5 o/oo isohaline. Apparent resupply was calculated to be never less than 50% of the inflowing riverine supply and often exceeded 80%.

Particulate biogenic silica levels in the peak biomass zone were less than 20 umole/L (Table 3), while the inflowing riverine dissolved silicate concentration was much higher (approximately 150 umole/L). Thus production of particulate biogenic silica did not balance the inferred uptake of dissolved silicate, indicating that a significant portion of the riverine dissolved silicate may be removed from the water column by deposition of particulate biogenic silica to the sediments or flushed out of the very low salinity region after being taken up by small diatoms which could not be trapped within this zone due to relatively low densities.

The deposited particulate silica may be resupplied to the water column through regeneration. In July 1986 when peak phytoplankton biomass occurred in the very low salinity region, dissolved silicate concentration in bottom water was higher than that at the surface (Table 7), suggesting that dissolved silicate is resupplied to the water column from sediment. In February 1987 when the peak biomass did not occur, the concentration at the surface was higher.

Some environmental factors affecting the silicic acid regeneration from the estuarine sediment was reported by Yamada and D'Elia (1984). They indicated that a substantial effect on the efflux of dissolved silicate is caused by the deposition rate of biogenic material to the sediment surface, the salinity of the overlying water and the ambient temperature. The release rate of dissolved silicate was independent of oxygen concentration of overlying water but was directly proportional to the amount of particulate biogenic silica applied to the cores. This suggests that dissolved silicate regeneration depends more strongly on recent deposition rates of the biogenic silica to the surface sediments

than on silicate dissolution rate in older, deeper sediments. When freshly deposited biogenic silica was incubated at various temperatures, efflux of dissolved silicate into the water was low at temperature below 15°C, but increased rapidly and exponentially above 15°C. Salinity had a marked effect on dissolved silicate release from the sediment cores. This release did not vary in direct proportion to the salinity, but instead was low at salinities below 10 o/oo, accelerated rapidly with salinity in the 10 to 20 o/oo range, and was high and relatively constant above 20 o/oo.

Consequently the highest rates of regeneration of dissolved silicate would be expected in the mesohaline regions of the estuary, during the warm months, and just after the period of maximum diatom abundance. During summer and fall, when temperatures and diatom biomass are high, the dissolution rate in the mesohaline regions will be high. Longitudinal transects of the estuary show typical summer and fall profiles of dissolved silicate (Fig. 17). Incoming river water has a highly dissolved silicate concentration. There is a peak phytoplankton biomass in the very low salinity region and the dissolved silicate concentrations become depleted coincident with the high diatom abundance. The dissolved silicate is resupplied in the mesohaline regions.

In addition to regeneration of dissolved silicate from sediment, regeneration can occur in the water column. Relatively high concentrations of particulate biogenic silica and the presence of fragmented diatom frustules (Anderson, 1986) in the water column adjacent to the position of maximum phytoplankton biomass implied that the dissolved silicate can be remineralized rapidly in the water column by the transition from a fresh to a more saline environment.

Relatively long residence time, during summer and fall when river discharge was low, may provide time for regeneration of dissolved silicate to occur both in the sediment and water column, and to allow the accumulation within the estuary. Destratification of the water column during spring tide (Hass, 1977), in addition to diffusion and tidal turbulence, may redistribute the regenerated silicate from the sediment or the deep water into the euphotic zone.

Nitrate

The distribution pattern of nitrate plus nitrite (hereinafter referred to as nitrate) from the surface water along the estuary axis shows apparent input signals within the estuary regardless of the occurrence of the chlorophyll peak in the very low salinity region. The nitrate concentration was increased within the 0 - 0.3 o/oo mixing segment during summer and autumn when the peak biomass occurred in the very low salinity region, and within the 0 - 3.0 o/oo mixing segment when the peak biomass did not occur in winter and spring (Fig. 14). There are several possibilities which may cause this.

Loder and Reichard (1981) demonstrated that mixing curves that are not linear - generally interpreted as indicative of non-conservative behavior (internal sources or sinks) - may be generated simply by temporal variations in the end member concentrations when the concentration is highly variable compared to the estuary's flushing time. It was noted that the use of mixing curves for the estuarine processes must be undertaken with an understanding of the river and ocean concentrate variability and its relationship to the estuary mixing

properties and flushing time. There is a possibility that the apparent input signals of nitrate in this study may be a result of the variability of the river end concentration.

Another possibility which may cause the increase in nitrate concentration is nitrification in the water column and/or sediment. Cerco (1981) reported the existence of nitrifying bateria both in the water column and sediment in the upper tidal James River estuary including Richmond (157 km upstream from NNS), Falling Creek (148 km upstream) and Hopewell city (110 km upstream). High nitrate concentration in this area was attributed to the nitrification. The increase in nitrate concentration in the very low salinity region of the James River estuary (between 80 to 110 km upstream) may be a result of nitrification of ammonia discharged from Hopewell city. The increase in nitrate concentration in the very low salinity of the Delaware estuary during summer and fall was also attributed to nitrification (Nixon and Pilson, 1983). Rapid ammonia removal was well matched with the increase in nitrate concentration within the same zone. Boynton et al. (1980) indicated that fluxes across the sediment - water interface represent an important nutrient source to the water column in summer when photosynthetic demand is high in the turbid portion of the Patuxent estuary. Denitrification is usually considered to be negligible in the water column except under conditions of elevated organic carbon and/or extreme oxygen depletion (Kessel, 1977). Relatively low concentration in the very low salinity region during winter and spring compared to the concentration during summer and fall (Fig. 14) is thought to be a result of dilution of ammonia by increasing river discharge.

Rapid decrease of nitrate within the 0.3 - 6.0 o/oo mixing segment

during summer and autumn (Appendix G) is probally a result of removal by high phytoplankton biomass in the very low salinity region (within the 0 - 0.5 o/oo mixing segment). During winter and spring, the concentration increased until the 3.0 o/oo isohaline and then decreased steadily down-estuary where the lowest concentration was achieved at NNS. Above the 6.0 o/oo isohaline levels, nitrate was mixed conservatively without regard to the occurrence of the peak biomass in the very low salinity region, indicating that any growth of phytoplankton in the lower estuary is supported by remineralization of dissolved organic nitrogen or by inputs from the sediment.

Autotrophic production in the very low salinity region may indirectly regulate the onset of the spring bloom at NNS by controlling the amount of nutrients available. During winter and spring when peak phytoplankton biomass did not occur in the very low salinity region, the nitrate concentration at NNS was relatively high (Appendix G). The spring bloom in February 1987 (Appendix C) occurred during the period of high nitrate concentration at NNS. Unlike the situation in the low salinity region, the concentrations of dissolved silicate and phosphate at NNS varied little with regard to the occurrence of the chlorophyll peak.

Phosphate

The behavior of dissolved inorganic phosphate over the duration of the study was generally similar to the pattern of dissolved silicate (Appendix G). When peak phytoplankton biomass occurred in the very low salinity region, most of the riverine phosphate supply was removed within

this zone, and then regenerated within the 0.5 - 15 o/oo mixing segment.

The initial removal of phosphate in the very low salinity region during summer and fall is probably due to biological uptake, because high phytoplankton biomass and dissolved silicate removal were observed in the same region. The buffering processes reported by Sharp et al. (1982) in the Delaware estuary and the removal by adsorption of phosphate from the solution onto solid phase (Liss, 1972) does not seem to be related to the initial decrease in phosphate concentration.

The positive relationship of phosphate with salinity in the mesohaline region during summer and fall, after removal in the very low salinity region, indicates that there is a source within the estuary resupplying the phosphate to the water column. A similar pattern was observed in the Ochlockonee Bay during spring by Kaul and Froelich (1984). Input may be a result of regeneration of organic-phosphate which was deposited on the sediment during the previous period. Relatively long residence time, during summer and fall when river flow was low, may provide time for regeneration to occur and allow the accumulation within the estuary.

The ratio of nitrate to phosphate concentration in the inflowing river was less than 5:1 (Appendix G), which is much lower than the Redfield ratio of 16:1. The relatively low ratio implies that nitrate is the critical limiting factor to phytoplankton growth and eutrophication in the James River estuary and adjacent coastal water, as mentioned by Ryther and Dunstan (1971) in the Long Island Bays. However, the nitrate concentration in the very low salinity region of the James River estuary was increased without regard to the occurrence of the peak biomass. This suggests that nitrate is not limited in the peak biomass zone and

phytoplankton preferentially uptake ammonia which may be present at high concentration due to waste discharged from Hopewell city. As a matter of fact, the data indicate that phosphate and dissolved silicate were more likely the limiting factors in the peak biomass zone (Appendix G).

4-4 Shoal Effect

Suisan Bay is a shallow and expansive embayment in northern San Francisco Bay. Summer maxima in total suspended particulate matter (Conomos and Peterson, 1977) and phytoplankton biomass (Arthur and Ball, 1981) often occur in this region. The flow over the shoals is known to be weaker than in the channel (Walters and Cheng, 1979). This probably allows phytoplankton to accumulate in the shoal areas.

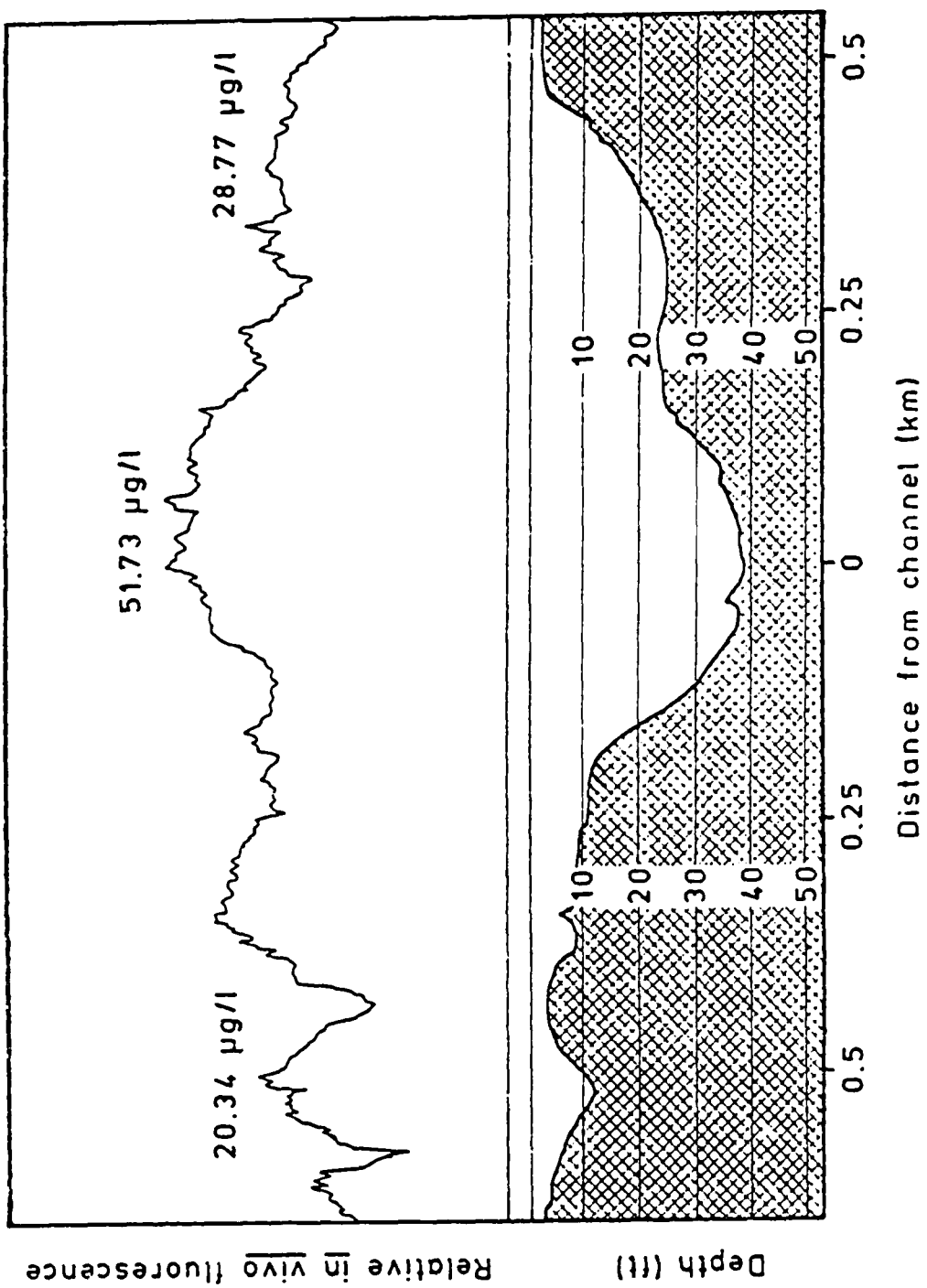
Cloern and Cheng (1981) felt that phytoplankton in the channel are severely limited by low light availability and growth rates are low, while phytoplankton in the lateral shoals grow rapidly. They further stated that the maximum phytoplankton biomass in the channel occurs when phytoplankton cells produced in the shoals are coupled (by lateral dispersion) with the turbidity maximum zone of the Suisun Bay, where the diatoms produced in the shoals are trapped. Because the turbidity maximum zone is dependent on river discharge, they indicated that the maximum phytoplankton biomass occurs only when river discharge falls within a critical range that positions the turbidity maximum zone adjacent to the productive shallow Suisun Bay. Cloern et al. (1983) showed that phytoplankton biomass during summers with normal river discharge is generally higher in the lateral shoals than in the channel of the Suisun Bay and a local chlorophyll maximum is present in the channel adjacent to the shallows. However, during drought, phytoplankton biomass was greatly reduced throughout the channel of the Suisun Bay, although chlorophyll concentration was still higher in the shoals than in

the channel.

The largest area of shallow shoals in the James River estuary is located near the mouth of the Chickahominy River (Fig. 1), approximately 65 km upstream from NNS. However, the peak phytoplankton biomass occurred further upstream between 89 and 103 km from NNS (Table 1), where the shoals are very narrow. In the highly productive shallow shoals of Suisan Bay (northern Sanfrancisco Bay), netritic diatoms (primarily dominated by Thalassiosira eccentrica and Skeletonema costatum) are produced, transported to the main channel, and trapped in the turbidity maximum zone. Peak phytoplankton biomass in the northern San Francisco Bay is comprised of more than 80% of the neritic diatoms. In contrast, the major source contributing to the peak biomass in the very low salinity region of the James River estuary is freshwater production. Freshwater species of diatoms such as Melosira sp and Cyclotella sp are reported as major component in the very low salinity region (Filardo and Dunstan, 1985). A sample selected from the peak biomass zone in June 1987 showed freshwater forms of diatoms having heavily silicified frustules as the major component. The diatoms were removed in salinities of 1.5 o/oo (Fig. 19), probably due to the osmotic stress encountered by the cells upon advection into the estuary. Therefore, the importance of shoals for causing the peak phytoplankton biomass in the James River estuary is different from that in the northern San Francisco Bay.

Phytoplankton biomass between the lateral shoals and channel near the position where the peak phytoplankton biomass occurred in the main channel was determined continuously by in vivo fluorescence measurement during the time of slack tide on 19 June 1987. The results show a pattern different from the case of the northern San Francisco Bay (Fig.

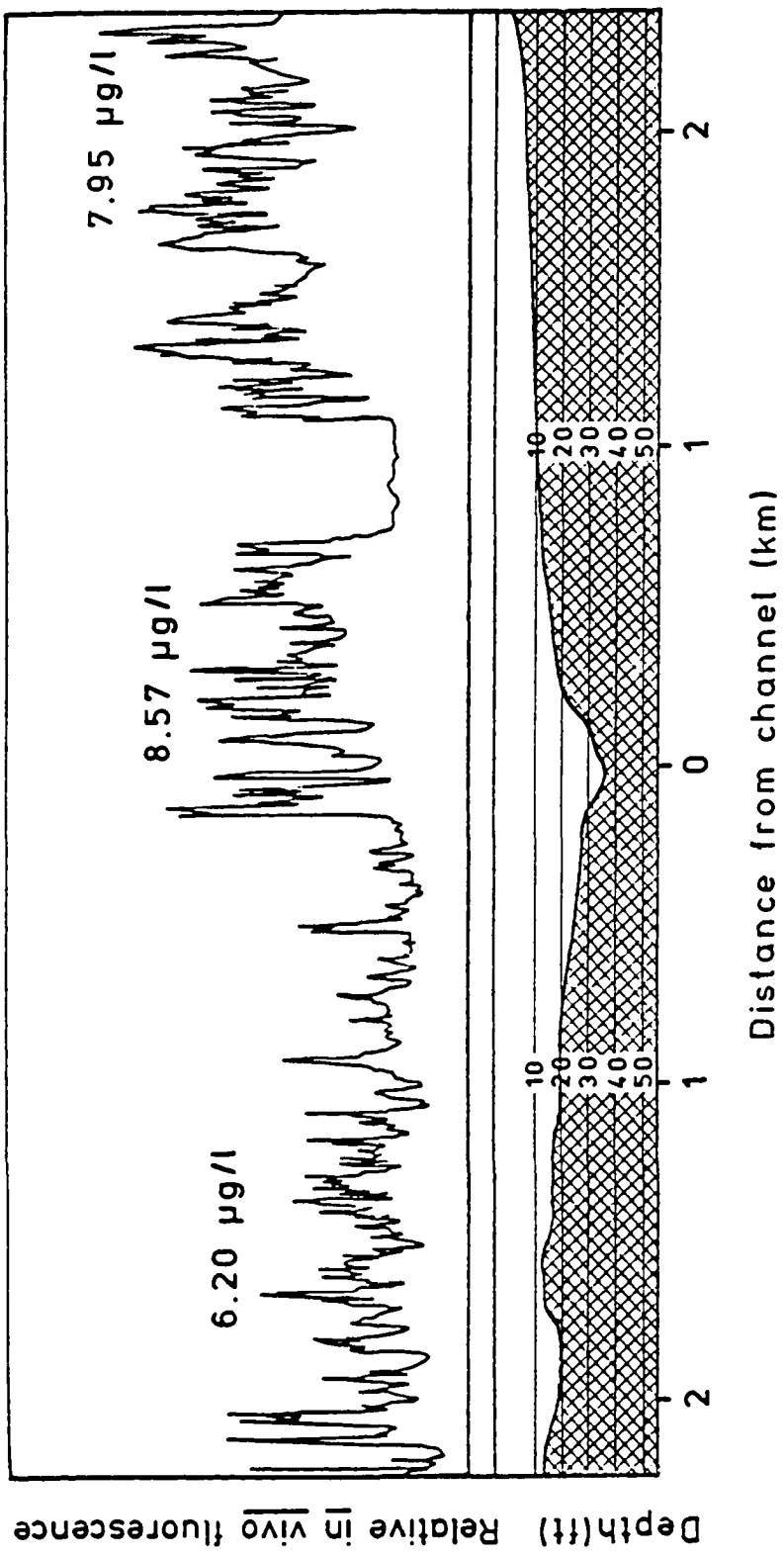
Figure 21. Phytoplankton biomass between the lateral shoals and channel during the time of slack tide near the position where the peak biomass occurred on 19 June 1987.



21). The biomass in the lateral shoals was much lower than in the channel. The extracted chlorophyll a concentration in the channel was also higher than in lateral shoals. The ratio of fluorescence values before acidification to fluorescence after acidification was relatively high in both channel (1.84) and shoals (1.82), suggesting that phytoplankton in both zones are in good physiological condition. The lateral gradients of biomass between the channel and shoals determined near the most expansive shoals, the mouth of the Chickahominy River (Fig. 22), also showed lower biomass in lateral shoals than in the channel.

Therefore, the peak biomass in the channel of the James River estuary does not appear to be caused by the transport from lateral shoals as reported for the northern San Francisco Bay.

Figure 22. Phytoplankton biomass between the lateral shoals and channel during the time of slack tide near the most expansive shoals on 19 June 1987.



CHAPTER 5

SUMMARY AND CONCLUSIONS

During summer and fall when river discharge was less than 120 m^3sec^{-1}, there was a peak phytoplankton biomass in the very low salinity region (less than 0.5 o/oo), and this peak represented five to ten times greater biomass than adjacent water further up and downstream. The peak biomass was hypothesized to be caused by hydrodynamic trapping (the same mechanism involved in the formation of the turbidity maximum) and by increased phytoplankton residence time during periods of low river discharge. It was also hypothesized that diatoms are selectively trapped in the turbidity maximum zone because their relatively high sinking rates closely balance the net upward vertical water velocity in the null zone. As river discharge increased during winter and spring, the peak biomass disappeared.

In addition to the above facts, this research provided the following new information:

1. The peak biomass occurs independent of the tidal state and the location of nutrient inputs.

2. The concentration and the width of the peak biomass decrease with increasing river discharge when river discharge is less than 120 m^3sec^{-1}.

3. Nutrient limitation is not responsible for the low biomass in the very low salinity region during the months of winter and spring,

indicating that physical, not chemical, factors are controlling the abundance within this zone.

4. During low river discharge, close balance of diatom sinking rates with the net upward water vertical velocity, relatively high netplankton biomass, exhaustion of dissolved silicate, relatively high ratio of particulate biogenic silica to POC and relatively low ratio of POC to chlorophyll a in the very low salinity region indicate that diatoms are selectively trapped within this zone.

5. As river discharge increases during winter and spring, the magnitude of the turbidity maximum increases, but the peak biomass disappears as a result of decreased phytoplankton residence time, decreased sinking rates of diatom due to increased water viscosity at low water temperature, and increased net-circulation which requires larger settling velocities to develop the peak biomass in the turbidity maximum.

6. There are some differences between the turbidity maximum zone and the location of the peak biomass. High biomass decreases very rapidly before the 1.5 o/oo isohaline, while the turbidity maximum zone encompasses a much broader area. Mass mortality due to osmotic stress placed on freshwater phytoplankton appears to be the best explanation for the rapid loss of biomass.

7. When peak biomass occurred in the very low salinity region, lower ratios of POC to PON and higher ratio of chlorophyll a to phaeopigments in the peak biomass zone than in the 2 o/oo isohaline region indicate that phytoplankton in the peak biomass zone are in better physiological condition.

8. The possibility that high biomass in the channel may be caused by the transport from shoals is improbable because the biomass in the shoals is much lower than in the channel.

9. The occurrence of the peak biomass and selective trapping of diatoms in the very low salinity region regulate the distribution pattern of nutrients in the estuary.

10. Dissolved silicate and phosphate are almost completely removed in the very low salinity region when peak biomass occurs within this zone and they are regenerated in the mesohaline region.

11. Concentrations of nitrate plus nitrite increase within the 0 - 0.3 o/oo mixing segment when the peak biomass occurs, and increase within the 0 - 3.0 o/oo mixing segment when the peak biomass does not occur during periods of high river flow.

12. Autotrophic production in the very low salinity region may indirectly regulate the onset of the spring bloom in the down-estuary by controlling the amount of nitrogen available.

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APPENDIX A. SUMMARY OF HYDROGRAPHIC DATA.

Appendix A. Surface salinity at NNS, the location of the 1 o/oo isohaline and average surface water temperature (°C).

Date	S(o/oo) at NNS	1 o/oo isohaline(km)	Temperature
Jul.86	23.0	75.7	29.5
Oct.86	23.6	79.8	19.5
Nov.86	-	72.1	-
Dec.86	17.8	52.1	7.4
Jan.87	-	-	5.0
Feb.87	15.3	35.9	4.8
Apr.87	2.3	6.2	13.4
Jun.87	-	60.0	29.4
Jul.87	20.6	73.2	29.6
Aug.87	25.0	78.0	28.8

APPENDIX B. SUMMARY OF TURBIDITY.

Appendix B. Turbidity determined by relative percentage transmissiom (%), light extinction coefficient (k^{-1}) and total suspended matter (TSM) from February through August 1987 (D = distance from NNS, S = surface water salinity).

February 27, 1987

D (km)	S (o/oo)	k (m^{-1})	TSM (mg/L)		Transmission (%)	
			Surface	Bottom	Surface	Bottom
0.8	15.32	1.86	25.8	42.3	35.0	32.0
13.9	7.70	2.66	29.5	65.3	25.0	27.5
36.6	0.78	7.42	74.9	113.1	5.3	3.4
49.6	0.02	6.15	40.5	46.3	8.0	7.5
97.4	0	3.58	37.5	38.2	12.0	12.0

June 19, 1987

D (km)	S (o/oo)	k (m^{-1})	TSM (mg/L)	Transmission (%)	
				Surface	Bottom
36.3	1.85	2.08	-	22.0	5.0
66.1	0.09	2.50	-	18.0	5.0
88.6	0	3.38	-	16.0	1.0
105.4	0	3.14	-	21.0	13.0

Appendix B. Continued

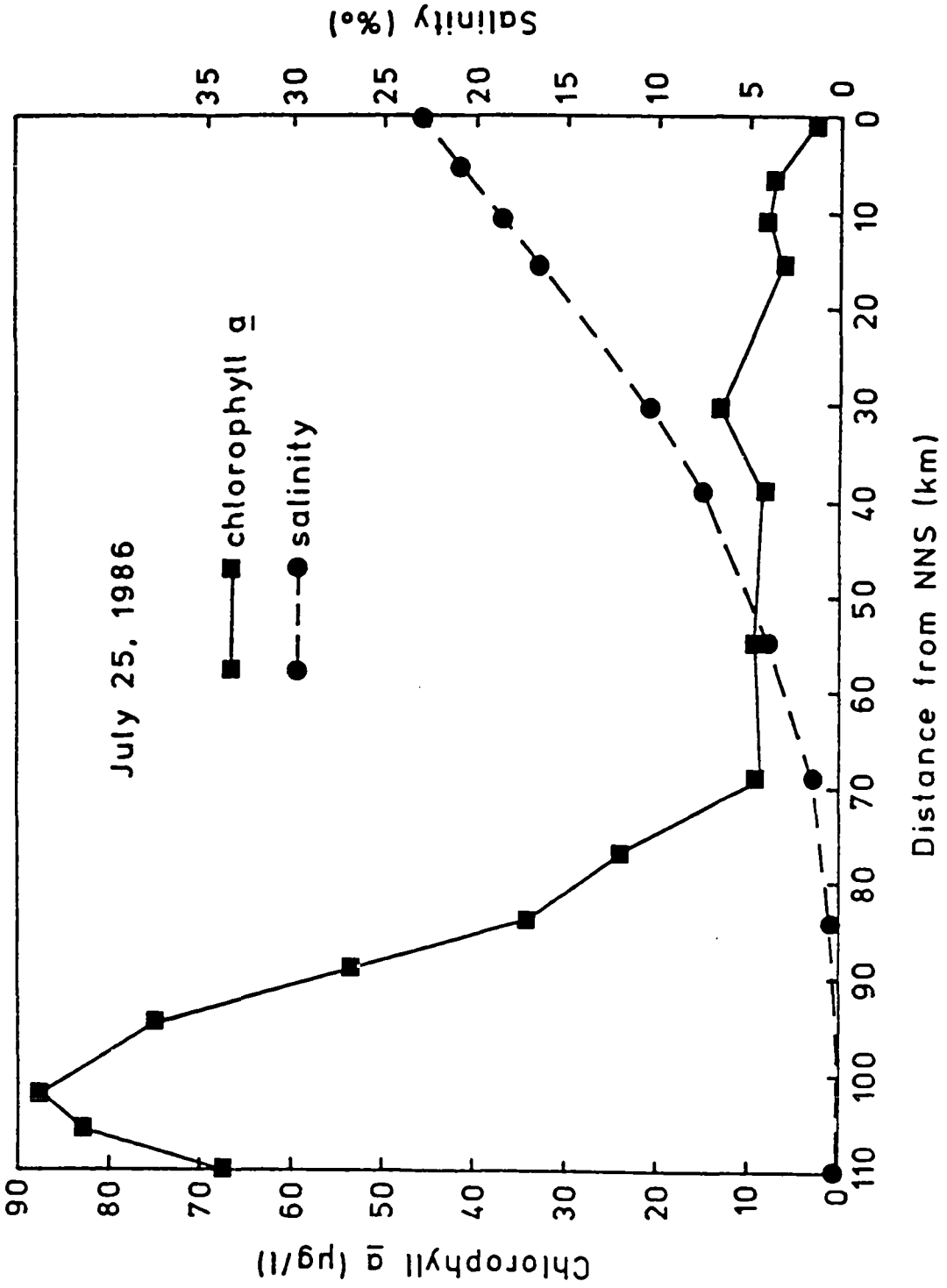
July 15, 1987

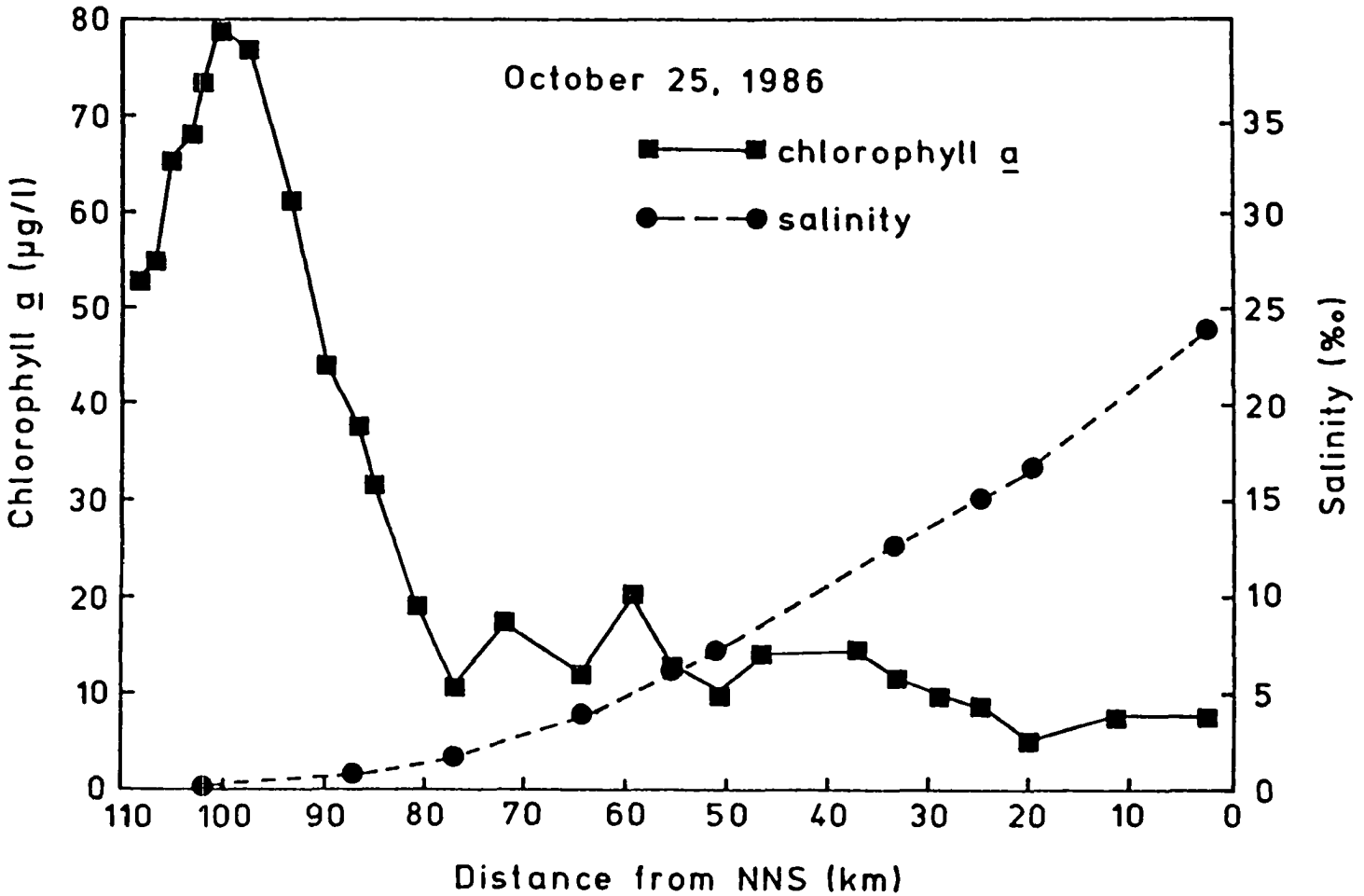
D (km)	S (o/oo)	k (m^{-1})	Surface TSM (mg/L)	Transmission (%)	
				Surface	Bottom
0	20.58	1.30	14.1	42.0	31.0
29.3	7.68	1.69	19.7	38.0	37.0
49.7	2.36	2.06	22.7	27.0	5.0
53.3	1.85	2.10	-	28.0	10.0
61.7	-	2.30	17.9	27.0	11.0
69.2	-	1.81	-	33.0	25.0
74.1	-	2.12	19.6	30.0	25.0
75.1	0.50	2.20	18.6	32.0	25.0
98.8	0.06	5.99	41.0	10.0	11.0

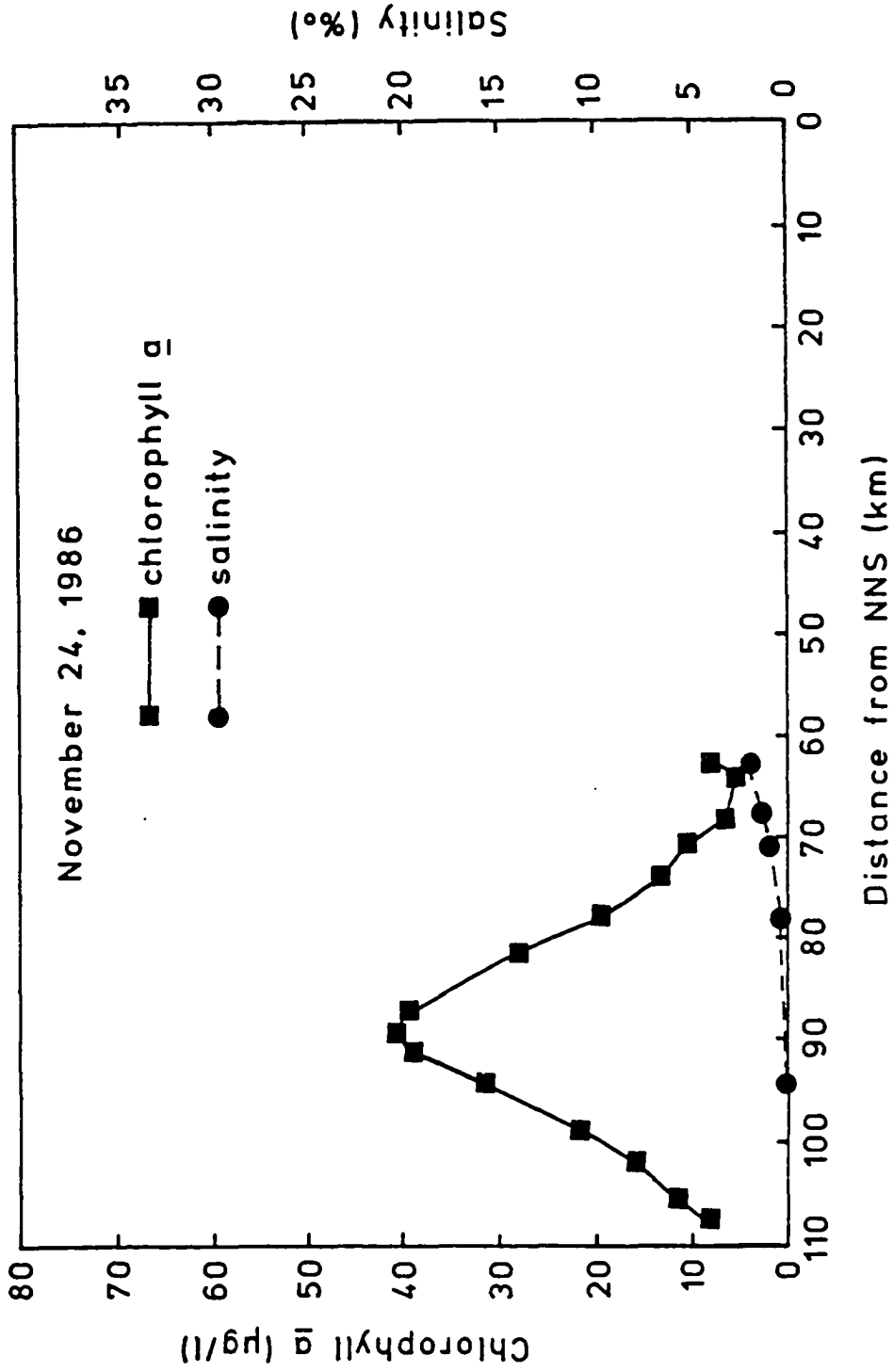
August 12, 1987

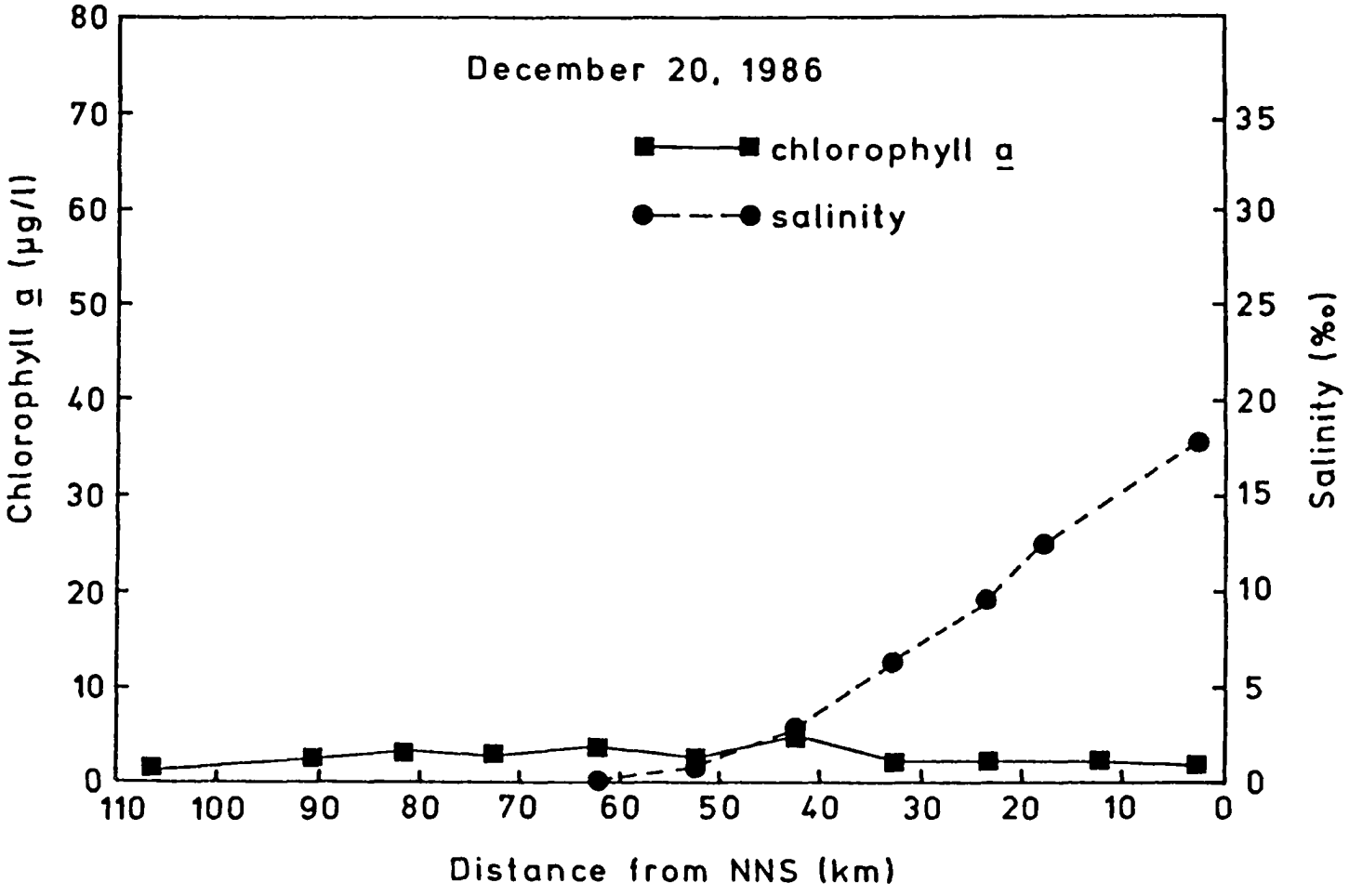
D (km)	S (o/oo)	k (m^{-1})	Surface TSM (mg/L)	Transmission (%)	
				Surface	Bottom
0	25.00	1.19	19.9	47.0	42.0
29.1	12.90	1.42	16.6	40.0	11.0
49.2	-	2.74	-	25.0	6.0
61.3	3.05	2.15	19.8	28.0	10.0
77.4	1.10	2.39	20.0	30.0	5.0
85.9	0.30	3.30	-	19.0	15.0
102.9	0.06	3.99	37.9	9.0	9.0
106.7	0	-	-	12.0	4.0

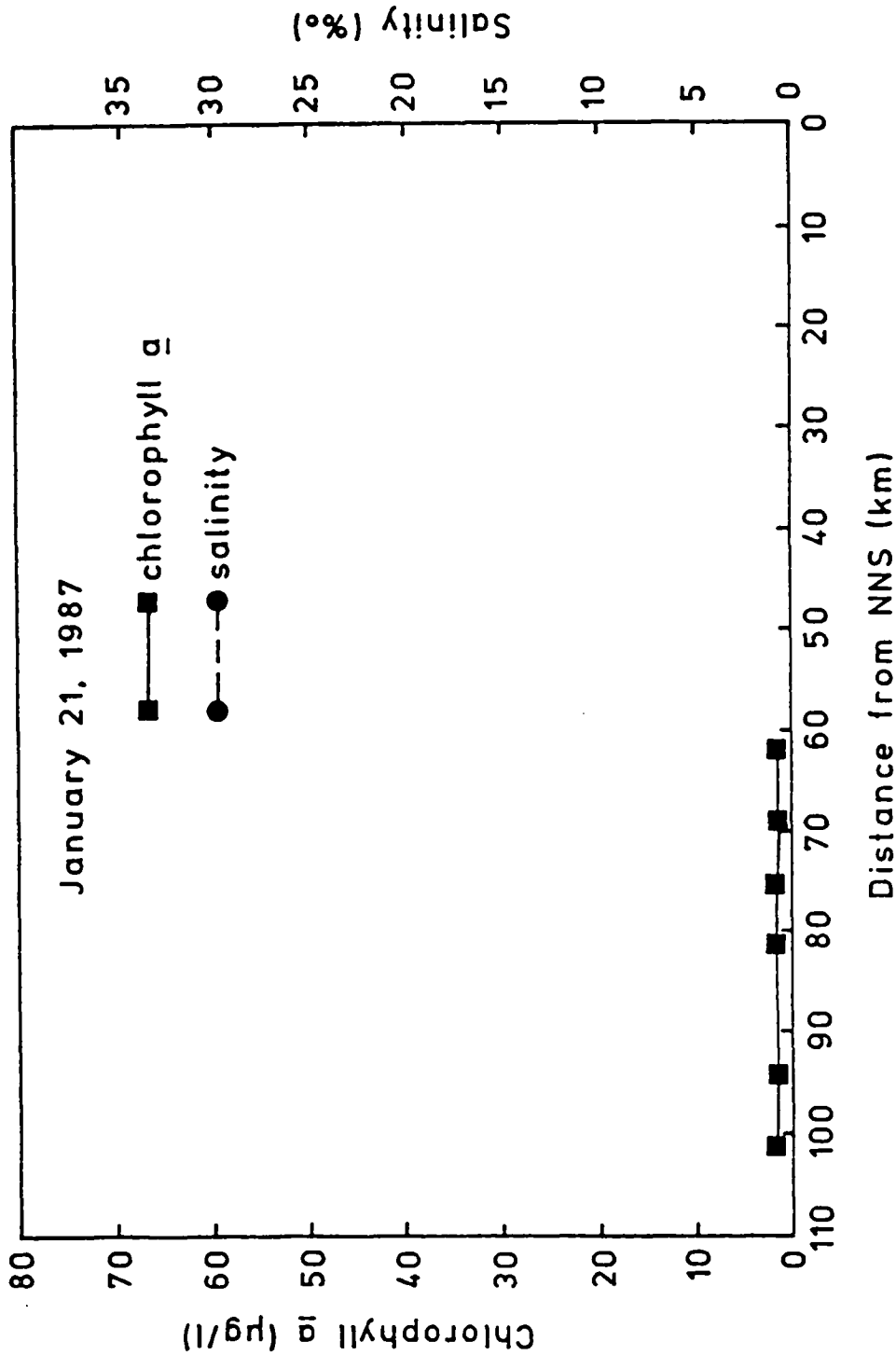
APPENDIX C. SUMMARY GRAPHS - PHYTOPLANKTON BIOMASS.

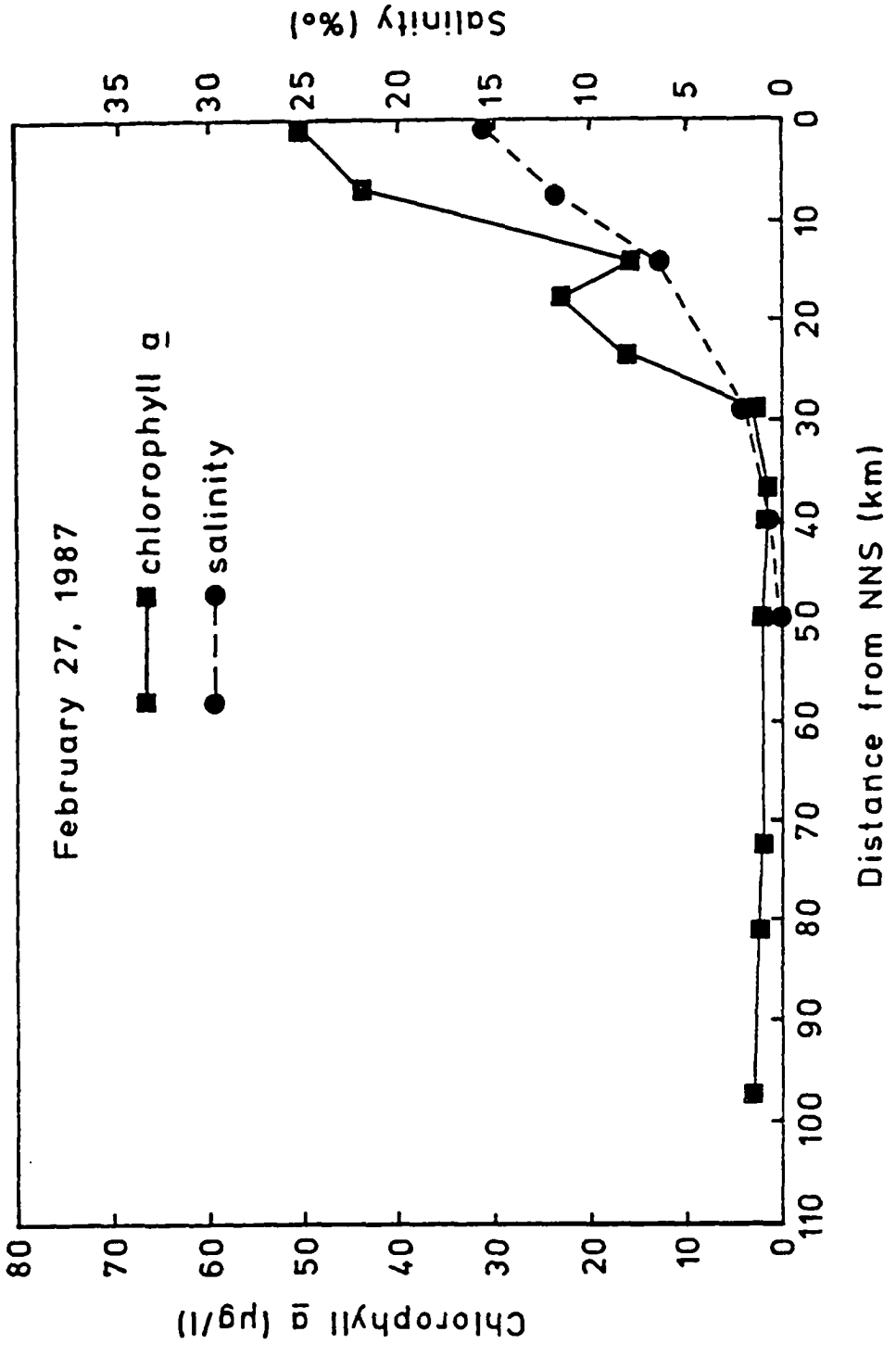


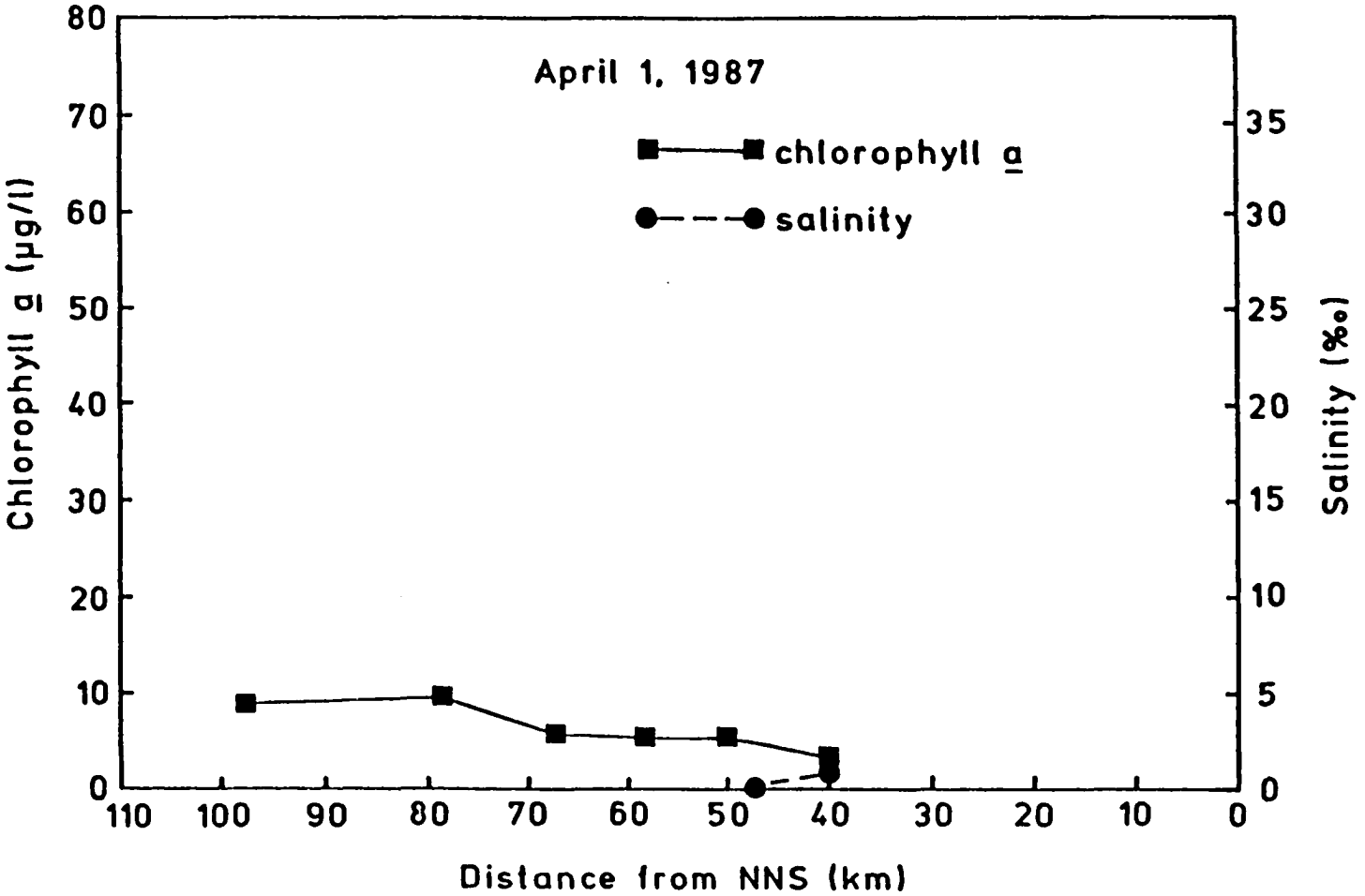


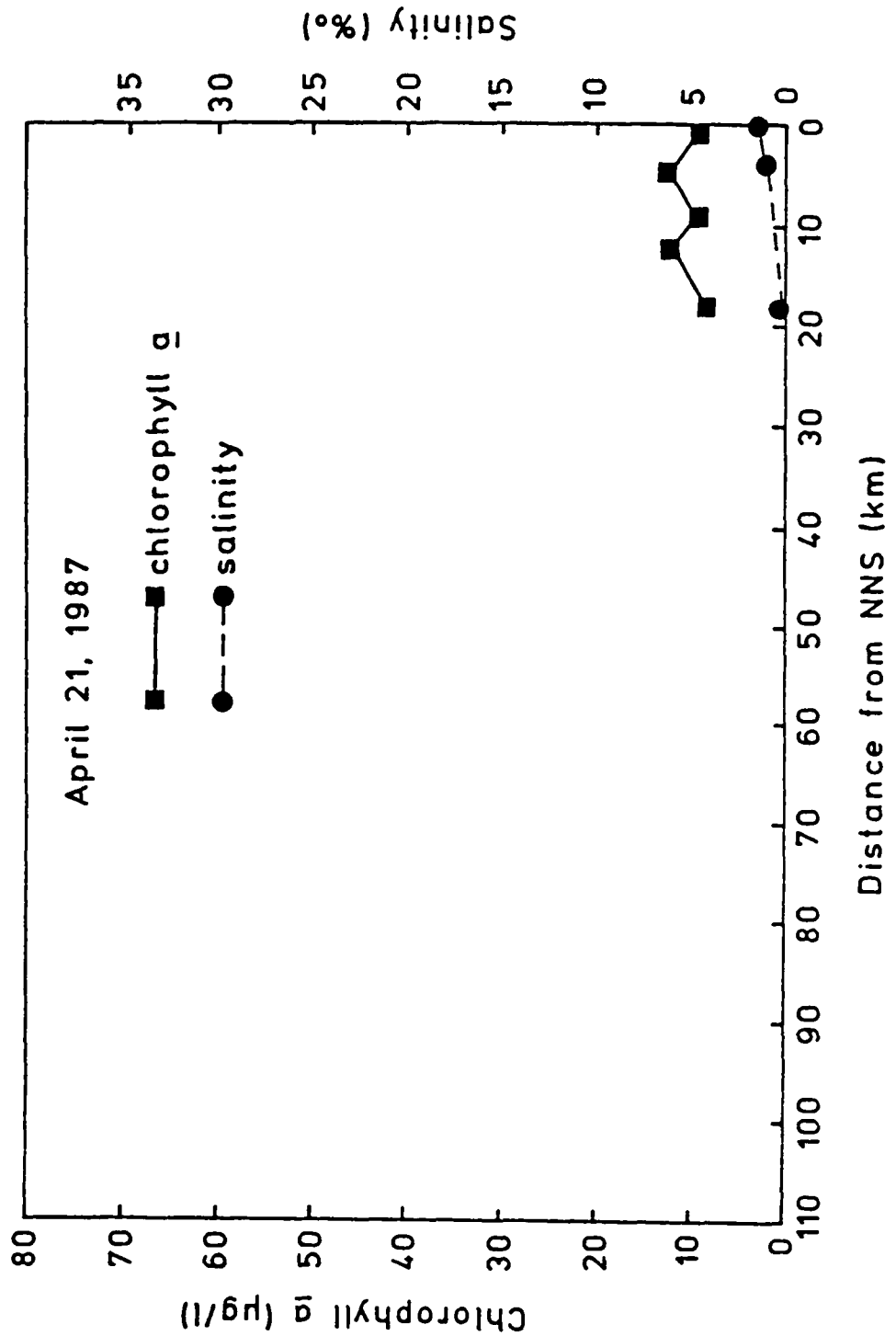


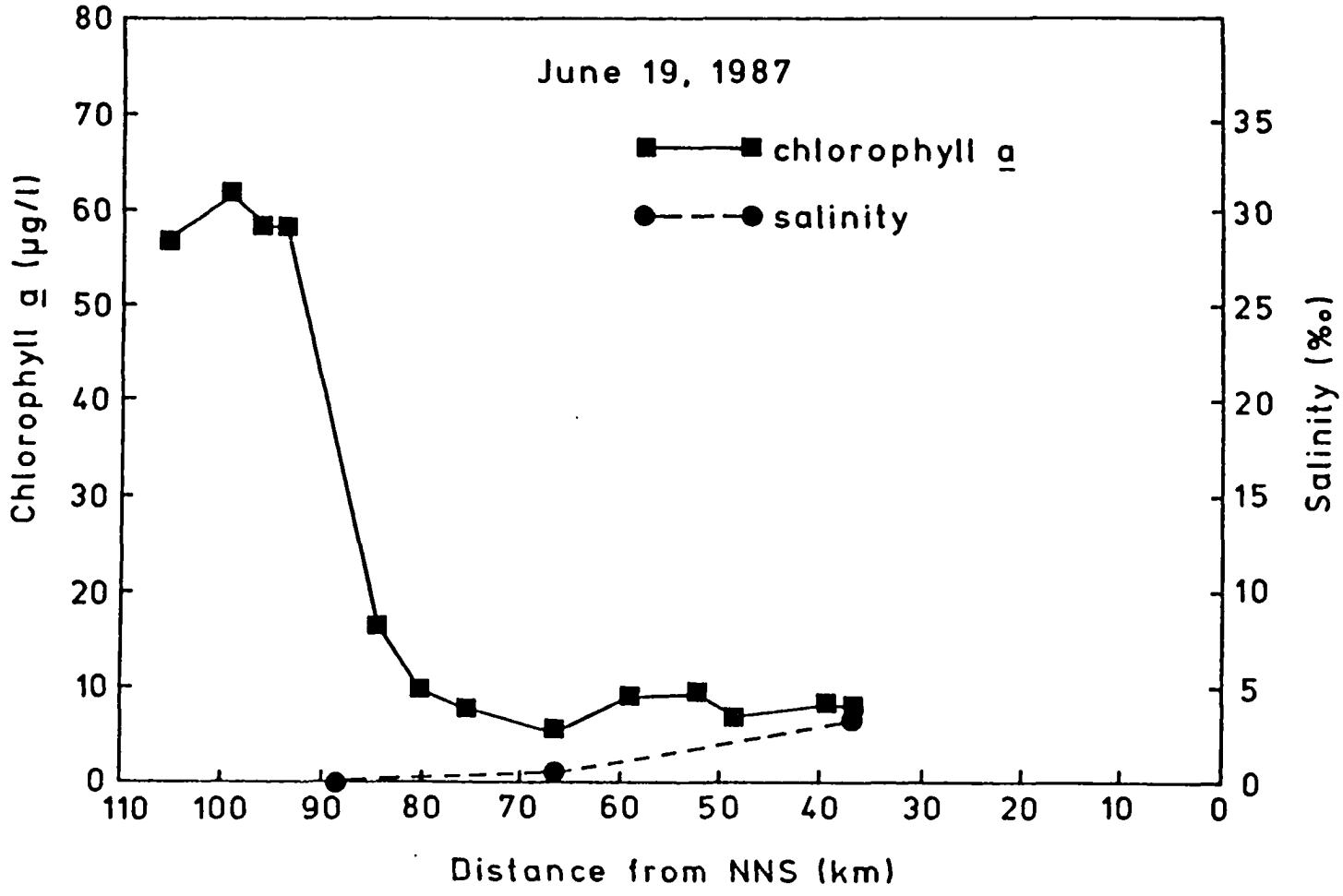


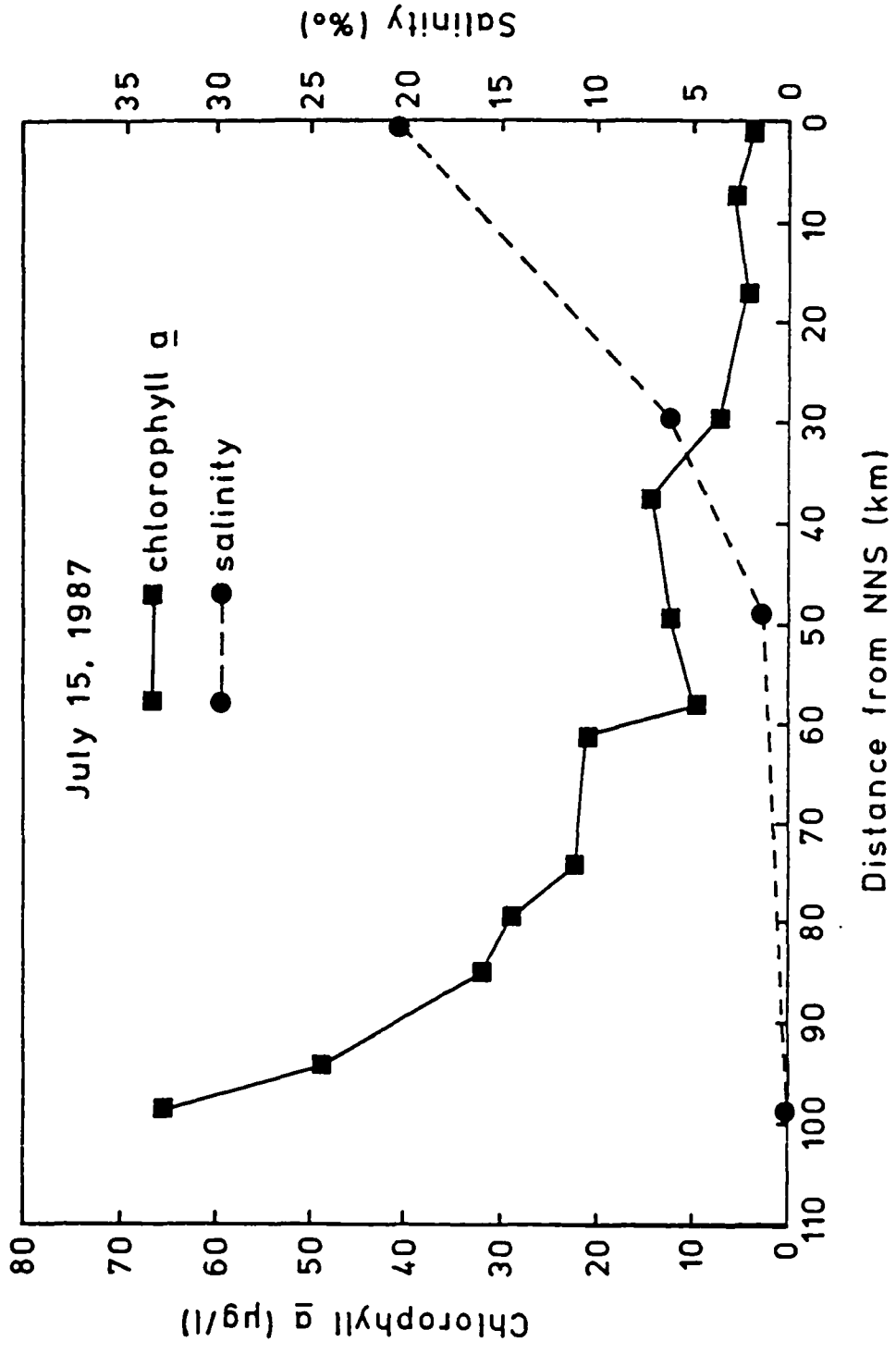


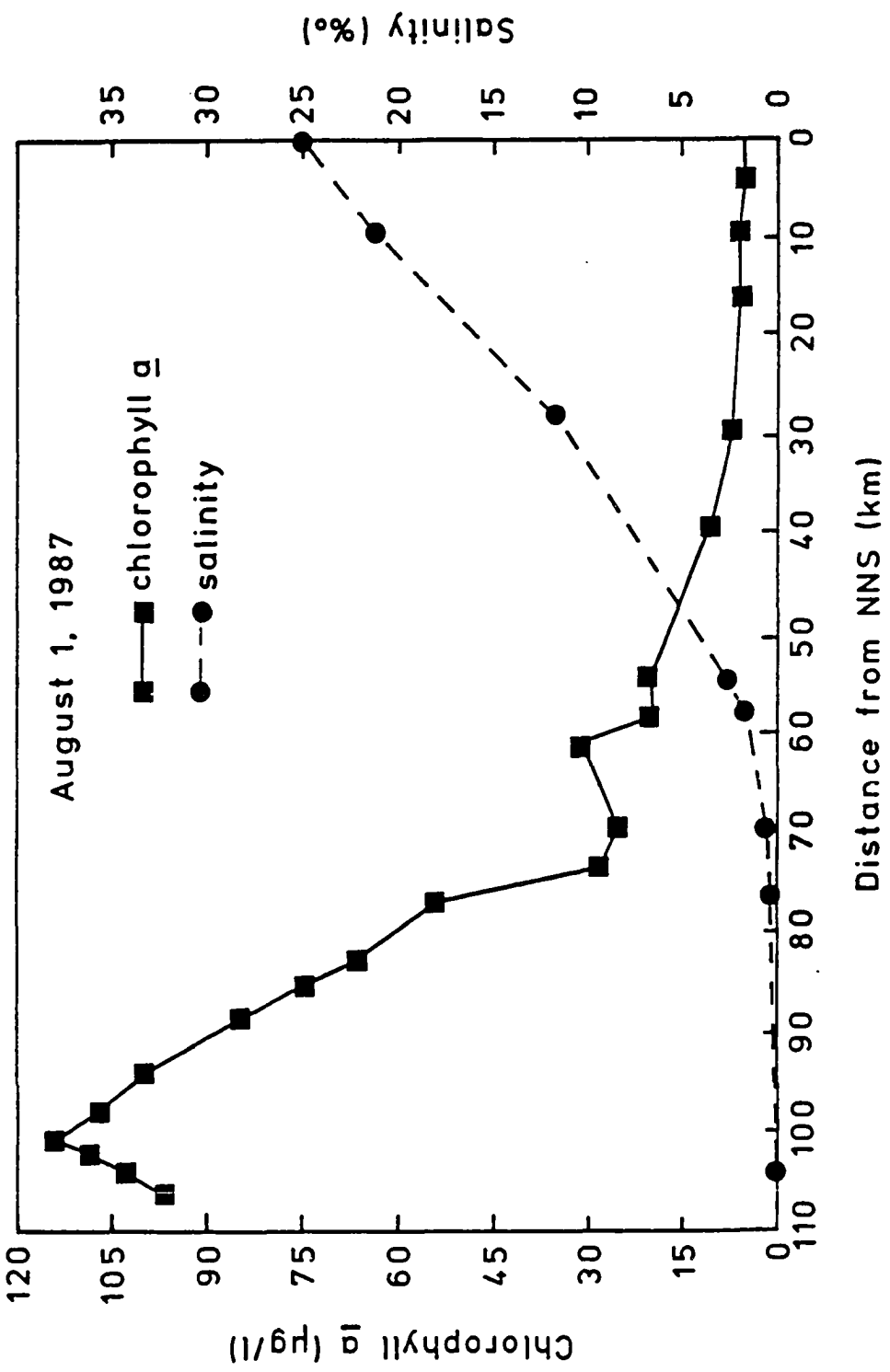












APPENDIX D. SUMMARY OF CHLOROPHYLL - POC RATIO.

Appendix D. The ratio of particulate organic carbon (POC) to chlorophyll a (POC/chl.a) from the surface water along the estuary axis.

July 25, 1986

D (km)	S (o/oo)	POC/chl.a
0.9	23.00	224.6
30.4	10.45	93.2
54.6	4.34	128.5
69.0	1.70	142.4
99.1	0.17	67.5

February 27, 1987

D (km)	S (o/oo)	POC/chl.a
0.8	15.32	48.9
13.9	7.70	180.5
28.4	-	449.7
49.6	0.02	998.8

April 1, 1987

D (km)	S (o/oo)	POC/chl.a
33.9	0.32	450.0
97.4	0	184.6

Appendix D. Continued.

June 19, 1987

D (km)	S (o/oo)	POC/chl.a
36.3	1.85	207.6
38.4	-	257.6
52.0	-	168.3
66.1	0.09	233.1
88.6	0	68.9
105.4	0	63.4

July 15, 1987

D (km)	S (o/oo)	POC/chl.a
29.3	7.68	237.1
49.7	2.36	124.1
61.7	-	109.9
74.1	-	107.9
98.8	0	65.9

August 12, 1987

D (km)	S (o/oo)	POC/chl.a
61.3	3.05	110.2
102.9	0.06	51.2

APPENDIX E. SUMMARY OF CHLOROPHYLL - PHAEOPIGMENTS.

Appendix E. Acid ratio of fluorescence values before acidification (Rb) to fluorescence after acidification (Ra) of extracts from the surface water along the estuary axis.

July 25, 1986

D (km)	S (o/oo)	Rb/Ra
0.9	23.00	1.66
30.4	10.45	2.04
54.6	4.34	1.83
69.0	1.70	1.71
99.1	0.17	1.89

October 25, 1986

D (km)	S (o/oo)	Rb/Ra
2.2	23.60	2.01
10.8	20.90	1.97
19.7	16.56	1.98
24.4	15.14	2.11
28.5	13.84	2.12
37.6	11.11	2.14
46.3	8.46	1.97
55.3	5.88	2.09
64.1	3.88	1.94
72.1	2.28	1.84
76.8	1.52	1.69
80.7	0.84	1.64
85.0	0.61	1.76
89.5	0.37	1.78
93.5	0.27	1.79
97.8	0.21	1.84
102.4	0.15	1.89
106.8	-	1.87

Appendix E. Continuted.

November 24, 1986

D (km)	S (o/oo)	Rb/Ra
63.4	1.87	1.61
73.4	0.87	1.59
81.0	0.30	1.69
87.4	0.17	1.89
94.1	0.12	1.88
101.8	0.10	1.81
107.3	0	1.69

December 20, 1986

D (km)	S (o/oo)	Rb/Ra
2.7	17.78	1.84
12.0	16.16	1.82
23.0	9.57	1.78
32.3	6.58	1.71
42.7	2.95	1.69
52.5	0.87	1.31
62.0	0.08	1.36
72.2	0.04	1.42
80.9	-	1.48
90.5	-	1.44
99.7	0	1.79
106.4	0	1.38

Appendix E. Continued.

January 21, 1987

D (km)	S (o/oo)	Rb/Ra
62.0	0	1.24
68.7	-	1.25
74.5	-	1.29
81.1	-	1.83
94.3	-	1.36
101.4	-	1.42

February 27, 1987

D (km)	S (o/oo)	Rb/Ra
0.8	15.32	2.06
13.9	7.70	1.63
28.4	3.37	1.59
36.6	0.78	1.23
49.6	0.02	1.26
97.4	0	1.60

Appendix E. Continued.

April 1, 1987

D (km)	S (o/oo)	Rb/Ra
39.9	0.32	1.46
49.9	-	1.50
58.3	-	1.45
66.3	-	1.36
78.0	0.02	1.57
97.4	-	1.73

April 21, 1987

D (km)	S (o/oo)	Rb/Ra
0	2.30	1.70
4.8	1.78	1.80
8.9	0.48	1.65
12.0	0.24	1.73
17.9	0.05	1.60

Appendix E. Continued.

June 19, 1987

D (km)	S (o/oo)	Rb/Ra
36.3	1.85	1.83
38.4	1.60	1.64
52.0	-	1.72
66.1	0.09	1.54
75.3	-	1.49
8.6	-	1.86
105.4	0	1.90

July 15, 1987

D (km)	S (o/oo)	Rb/Ra
0	20.58	1.76
17.0	-	1.84
29.3	7.68	1.86
37.8	-	1.81
49.7	2.36	1.88
61.7	-	2.05
74.1	-	1.85
85.2	-	1.84
98.8	0.06	1.91

Appendix E. Continued.

August 12, 1987

D (km)	S (o/oo)	Rb/Ra
0	25.00	1.76
9.3	22.56	1.83
29.1	12.90	1.78
39.5	9.30	1.91
55.0	4.54	1.88
61.3	3.05	1.95
77.4	1.10	1.90
85.9	0.30	1.92
102.9	0.06	1.90

APPENDIX F. SUMMARY OF PARTICULATE ORGANIC MATTER.

Appendix F. Particulate organic carbon (POC) and nitrogen (PON), particulate biogenic silica (PBS) and the ratio of POC to PON by atom. The unit is ug/L.

July 25, 1986

D (km)	S (o/oo)	PBS	PON	POC	POC/PON
0.9	23.00	-	38.9	700.9	21.02
30.4	10.45	-	124.2	1700.5	15.98
54.6	4.34	-	56.3	1242.9	25.76
69.0	1.70	-	74.3	1290.2	20.25
99.1	0.17	-	767.6	5577.4	8.48

February 27, 1987

D (km)	S (o/oo)	PBS	PON	POC	POC/PON
0.8	15.32	519.0	179.1	2436.1	15.87
13.9	7.70	6.0	83.0	2793.9	39.25
28.4	-	-	ND	1475.0	-
36.6	0.78	3.0	ND	3383.0	-
49.6	0.02	3.0	ND	2157.5	-

April 1, 1987

D (km)	S (o/oo)	PBS	PON	POC	POC/PON
39.9	0.32	-	59.4	1498.5	29.45
97.4	0	-	107.4	1591.5	17.29

Appendix F. Continued.

June 19, 1987

D (km)	S (o/oo)	PBS	PON	POC	POC/PON
36.3	1.85	-	122.4	1696.3	16.17
38.4	-	-	151.2	2395.4	18.49
52.0	-	-	126.5	1565.2	14.43
66.1	0.09	-	66.0	1344.9	23.77
88.6	0	-	458.0	3999.8	10.19
105.4	0	-	419.9	3592.2	9.98

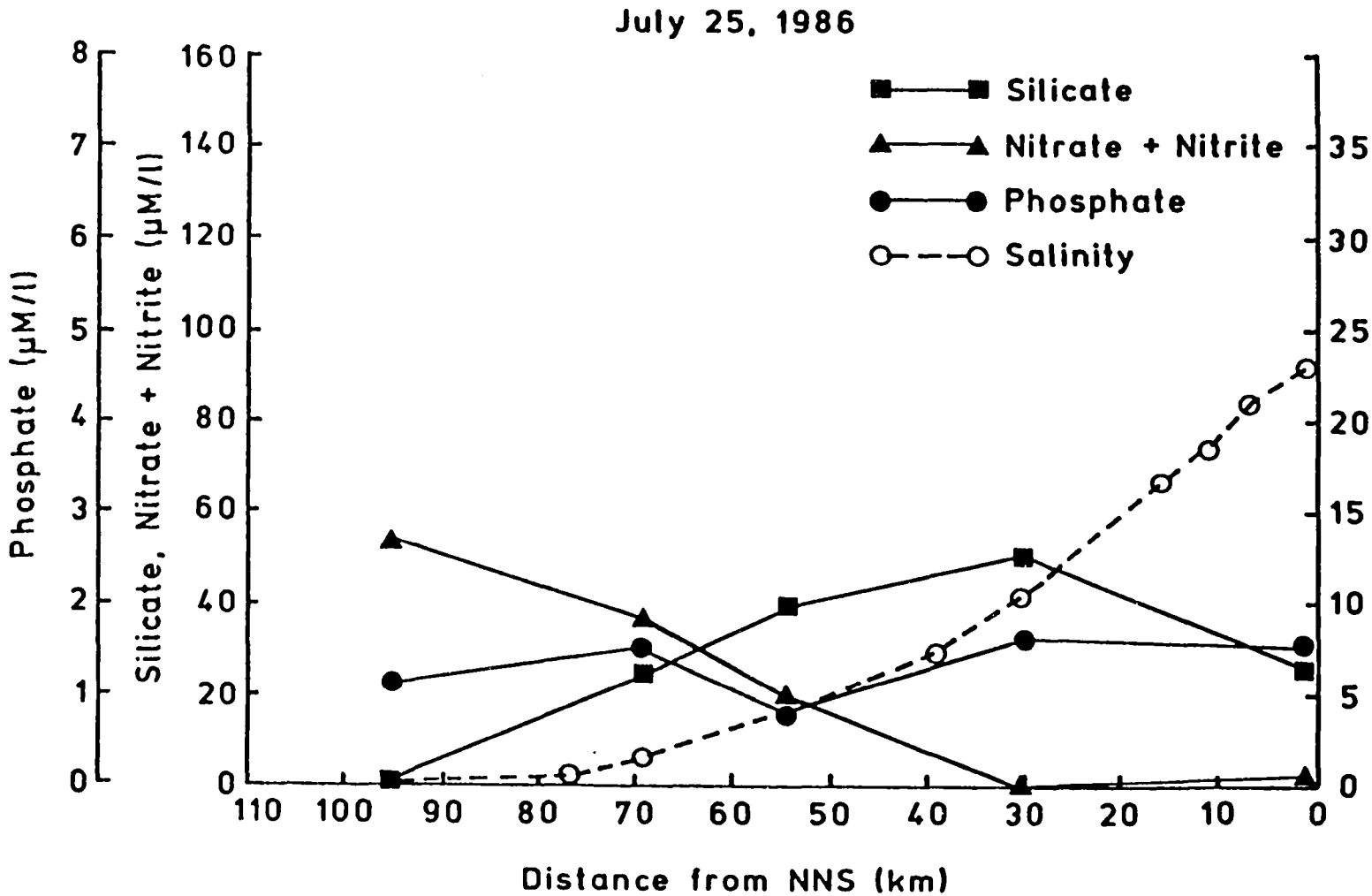
July 15, 1987

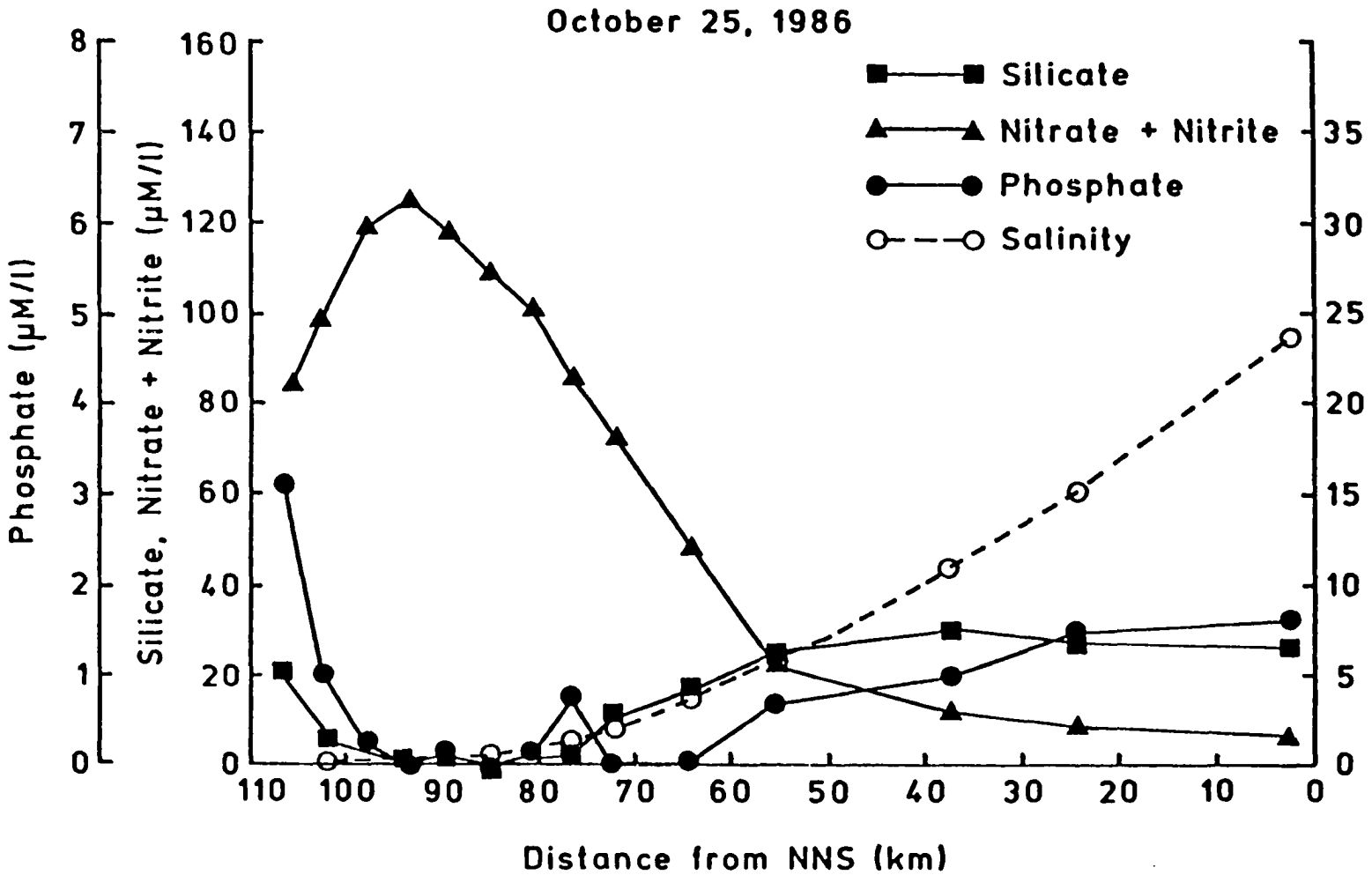
D (km)	S (o/oo)	PBS	PON	POC	POC/PON
29.3	7.68	15.0	186.5	2676.5	16.75
49.7	2.36	27.6	188.4	2337.8	14.48
61.7	-	21.0	249.4	3515.6	16.45
74.1	-	33.6	238.4	3579.3	17.52
98.8	0.06	1204.2	813.7	6439.4	9.23

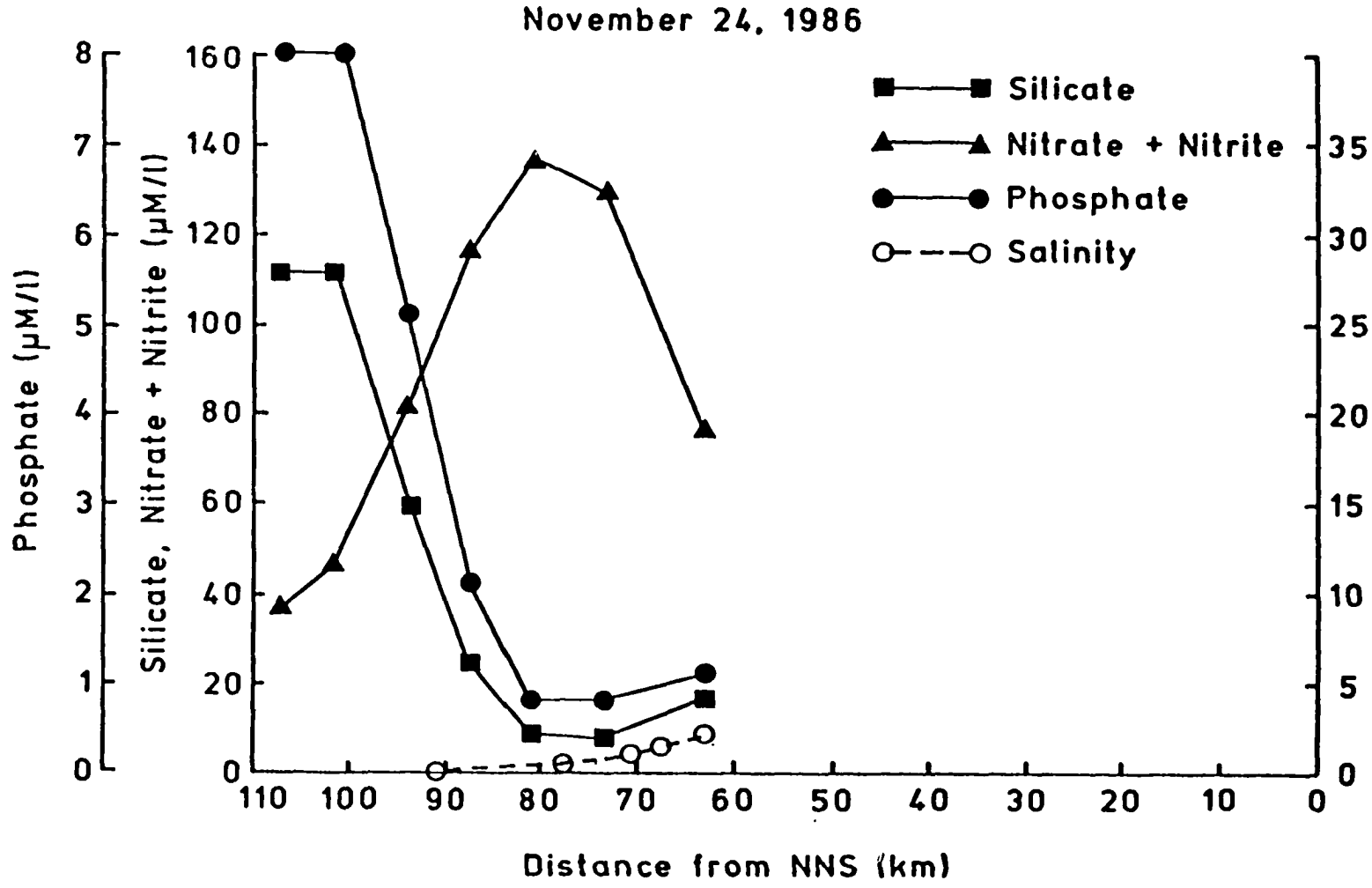
August 12, 1987

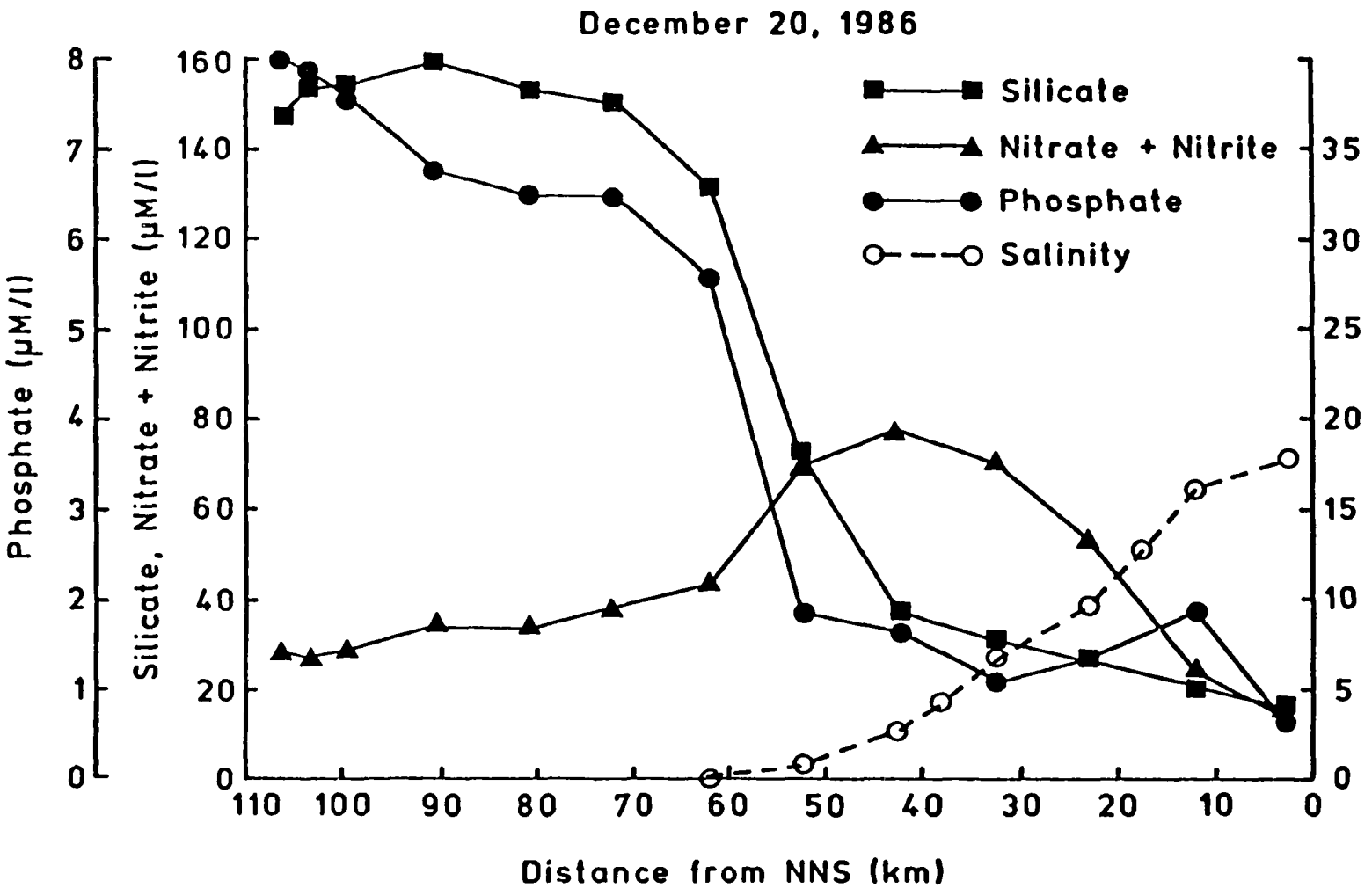
D (km)	S (o/oo)	PBS	PON	POC	POC/PON
61.3	3.05	21.0	316.6	3466.5	12.77
102.9	0.06	975.6	563.7	5574.6	11.54

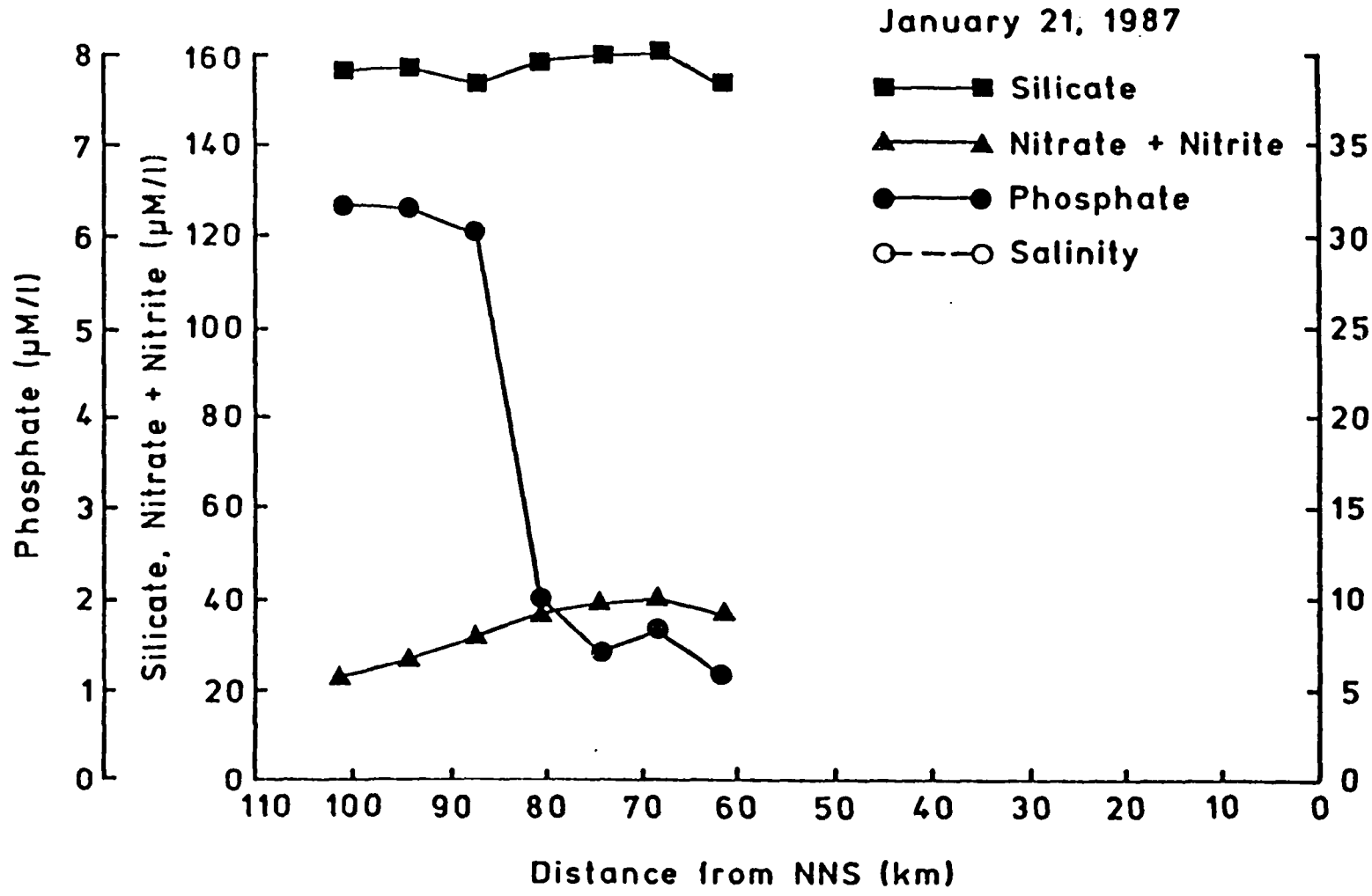
APPENDIX G. SUMMARY GRAPHS - NUTRIENTS I.

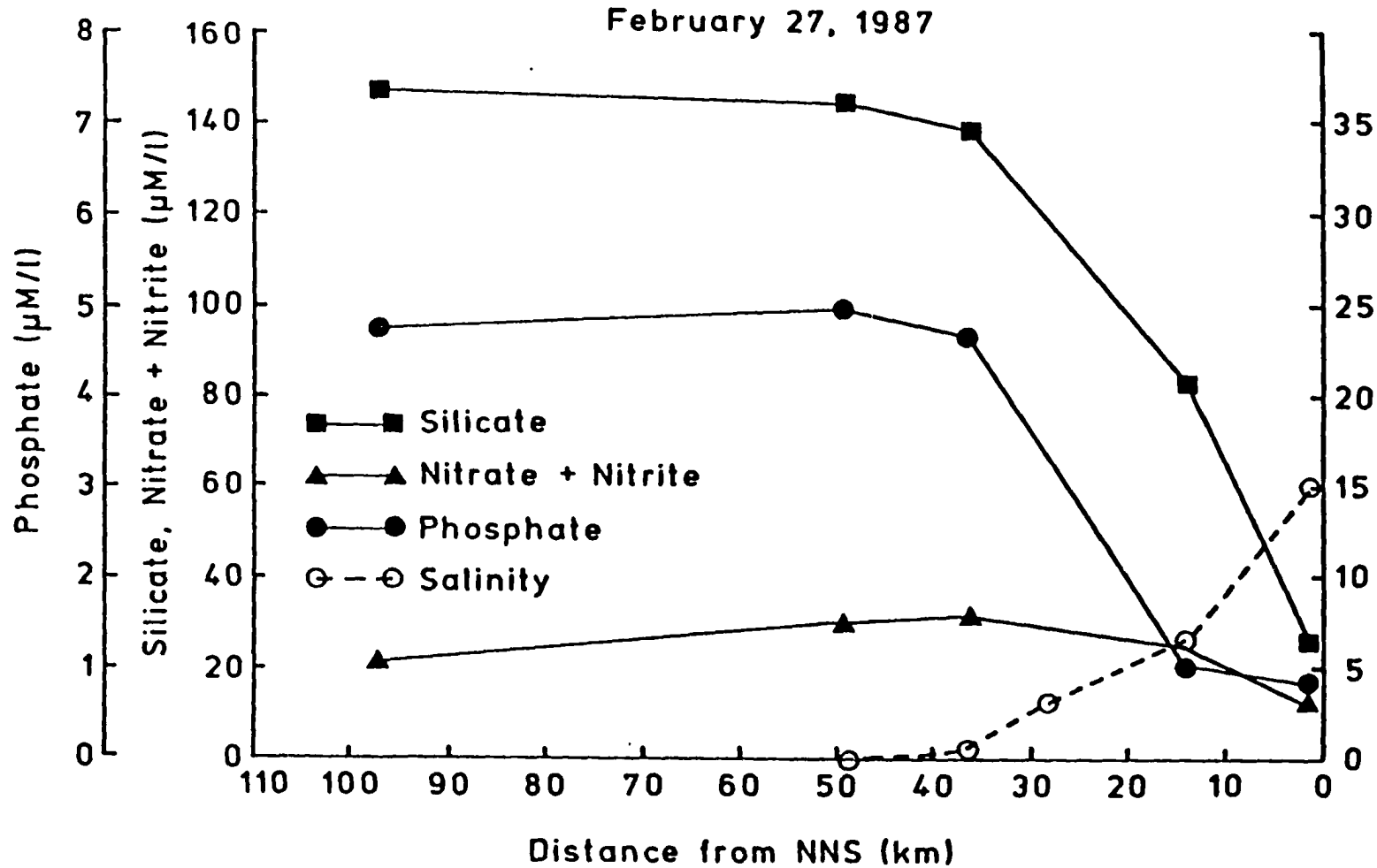




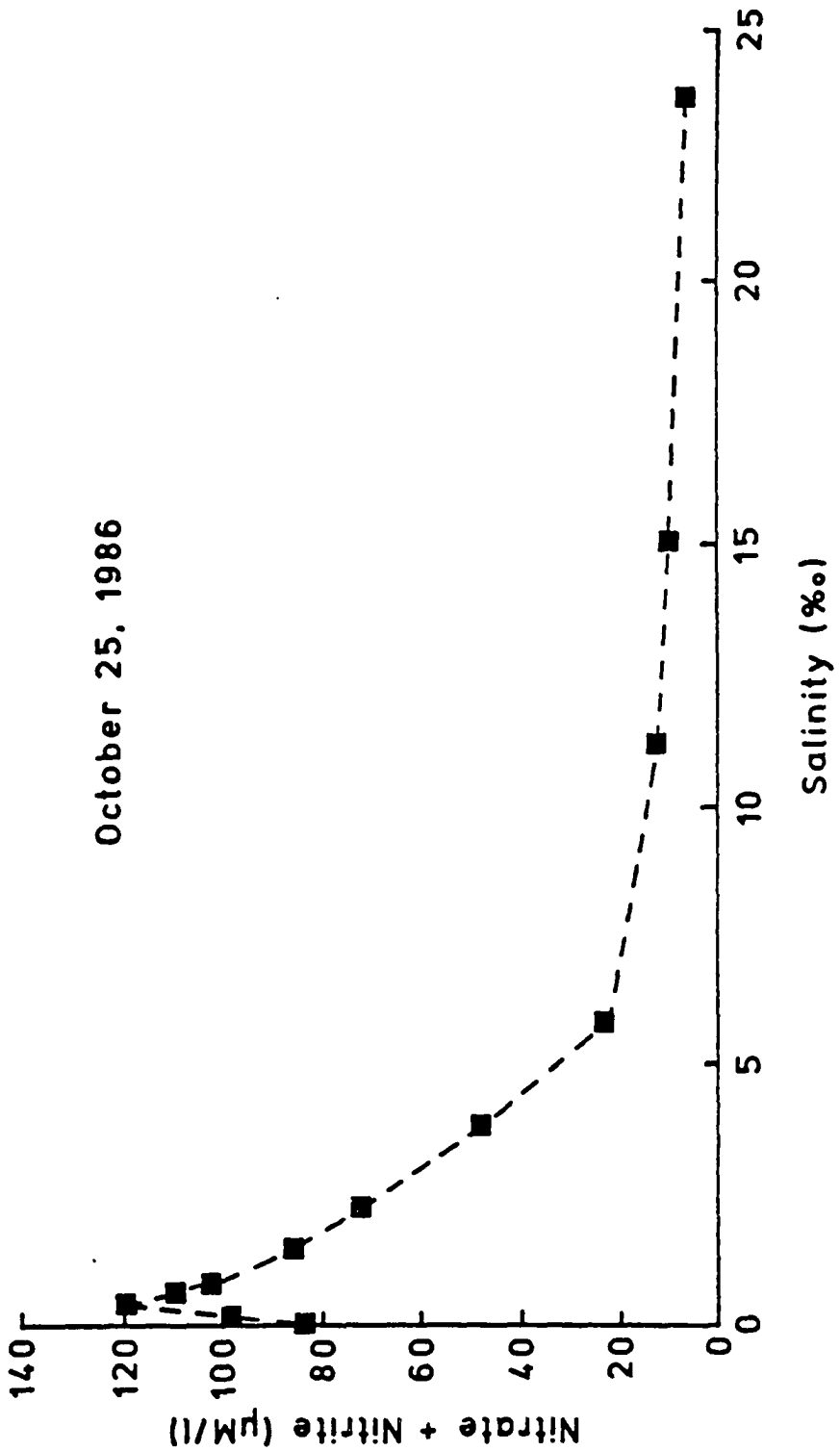


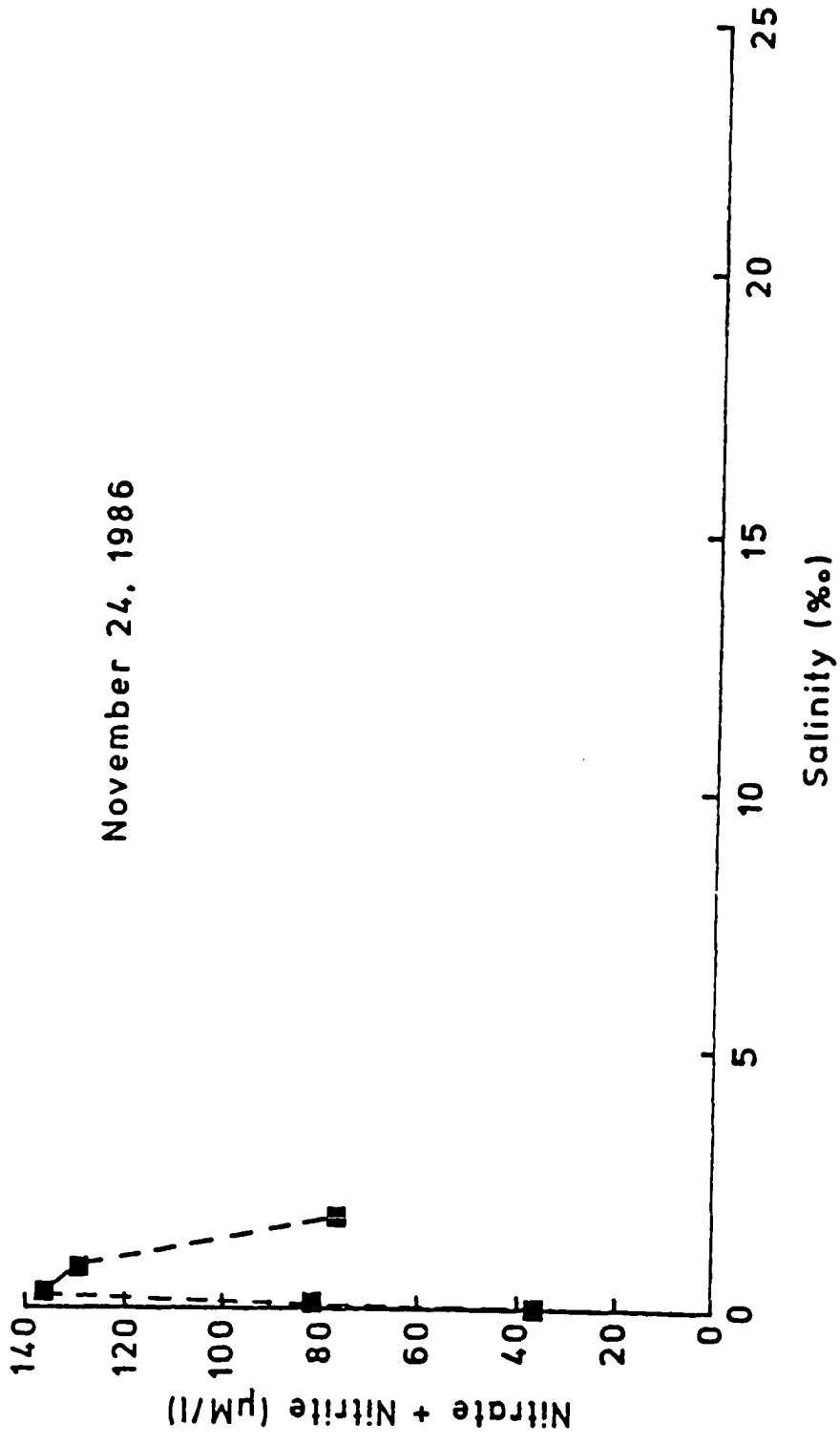


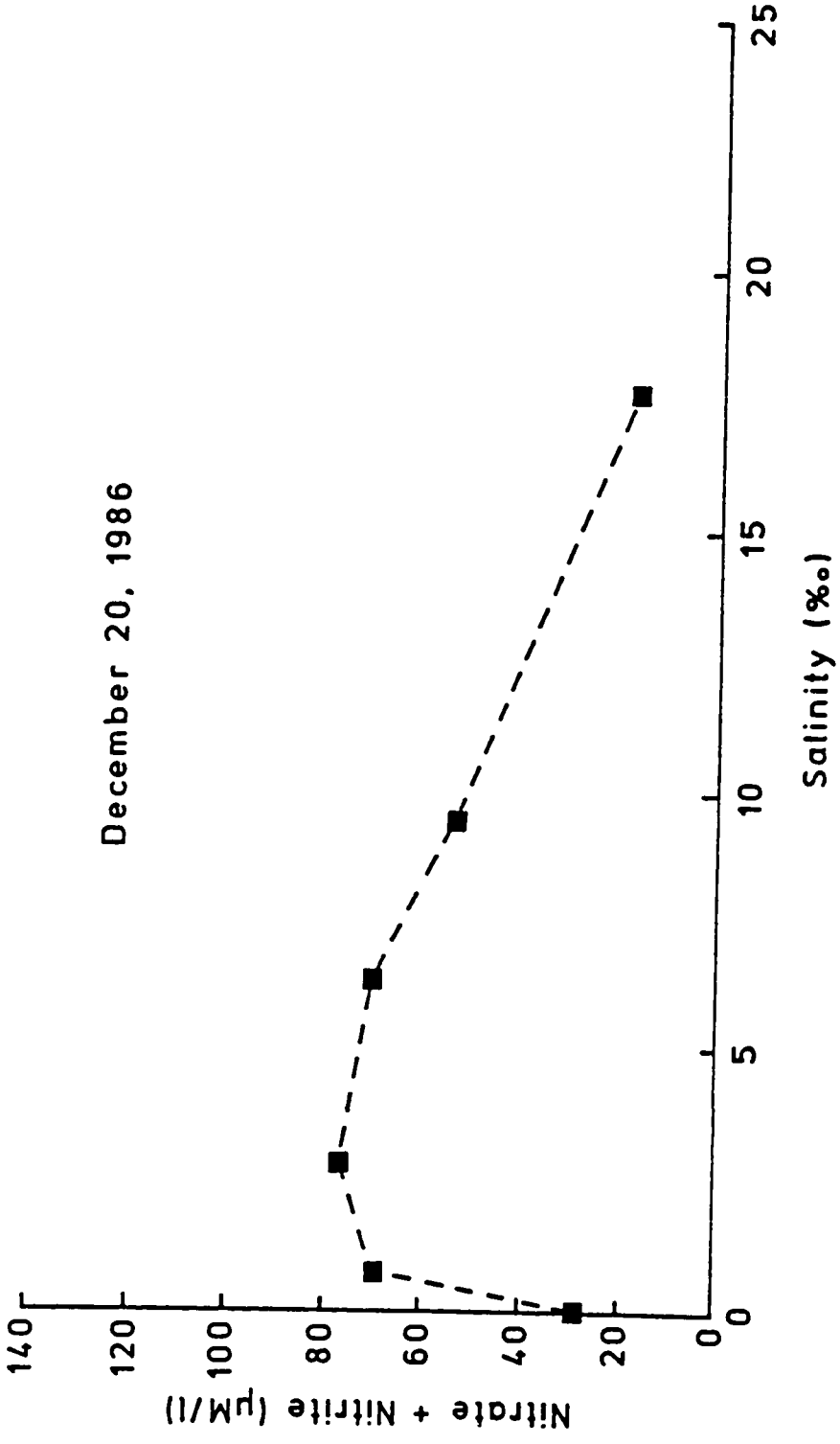


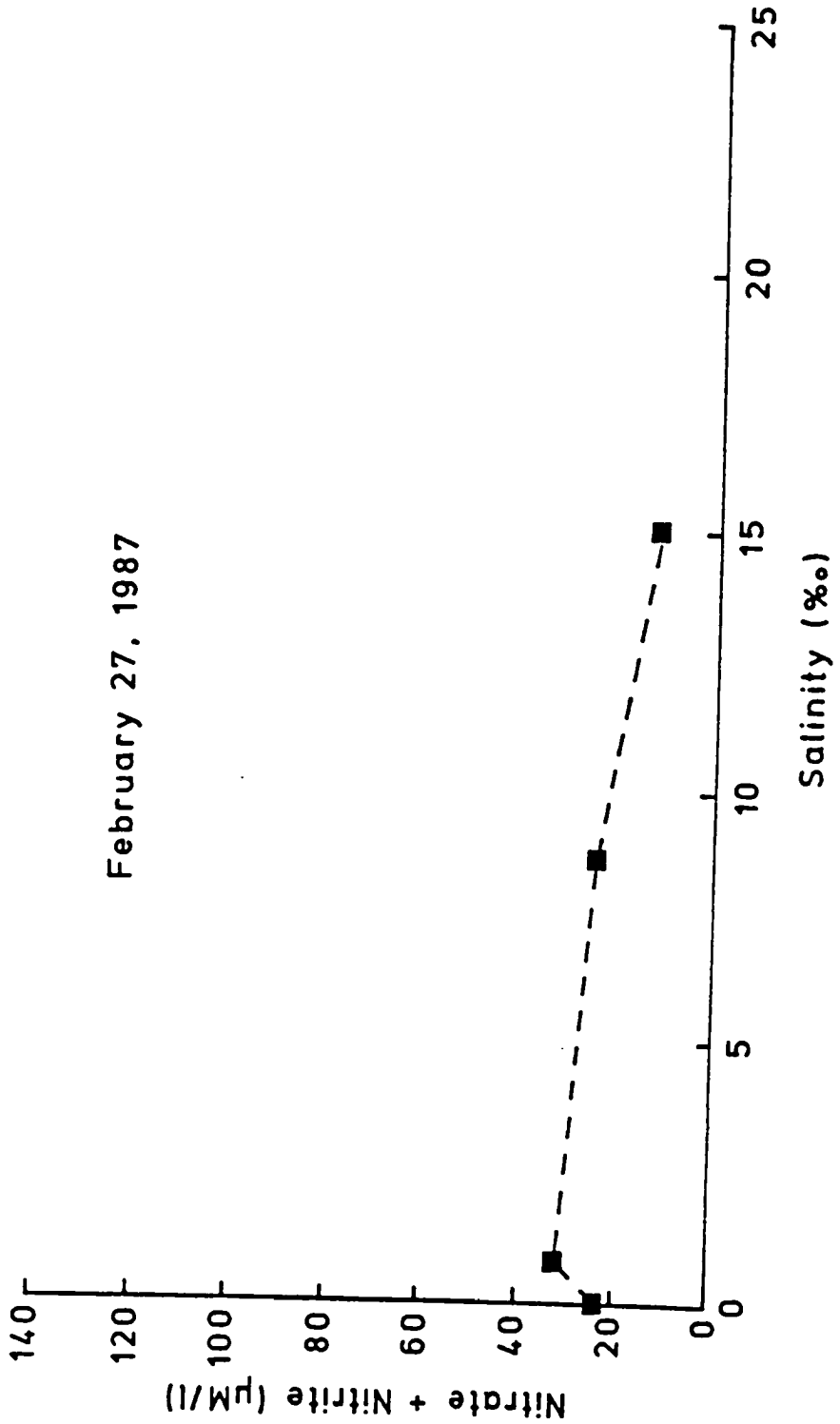


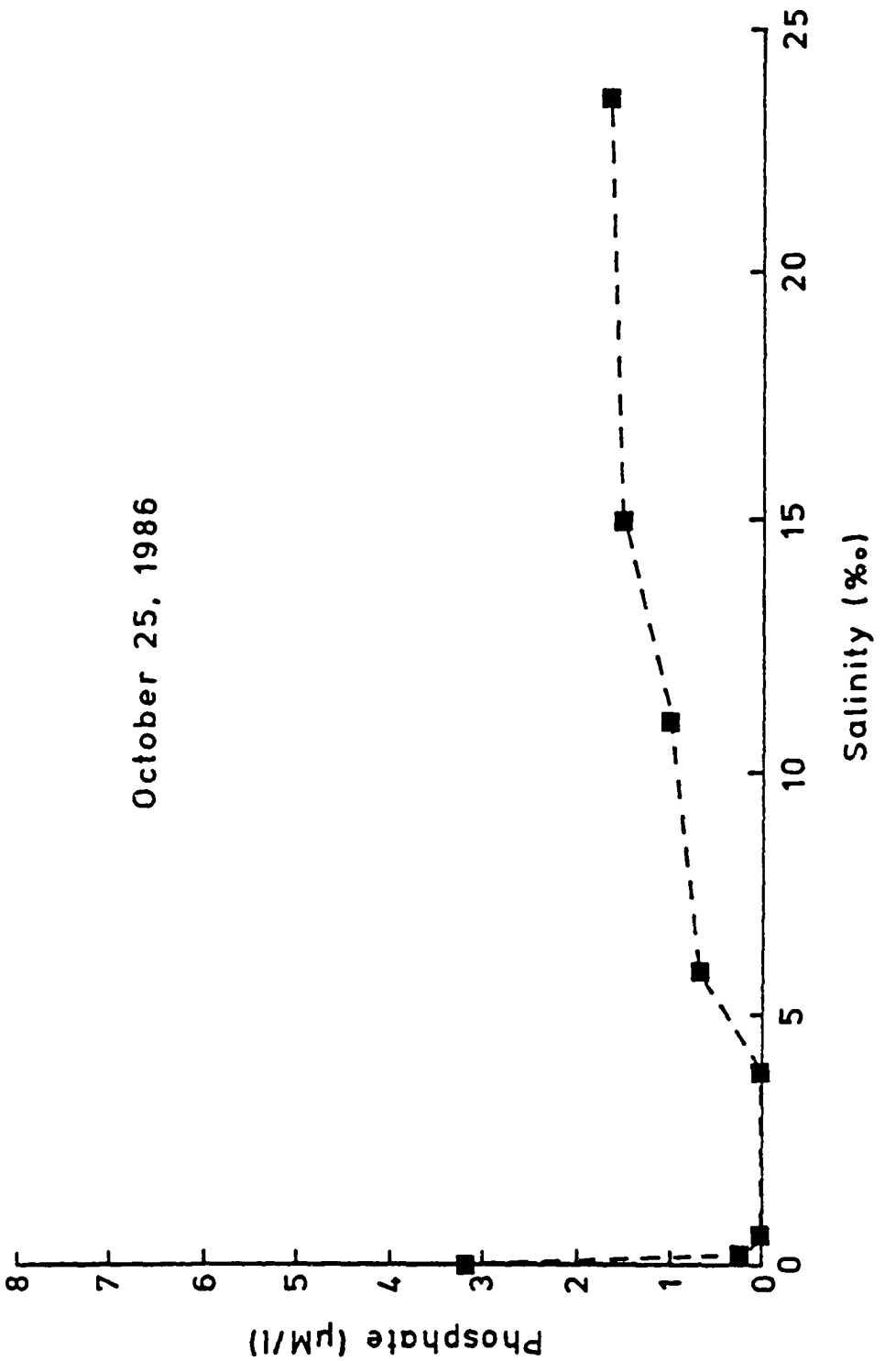
APPENDIX H. SUMMARY GRAPHS - NUTRIENTS II.

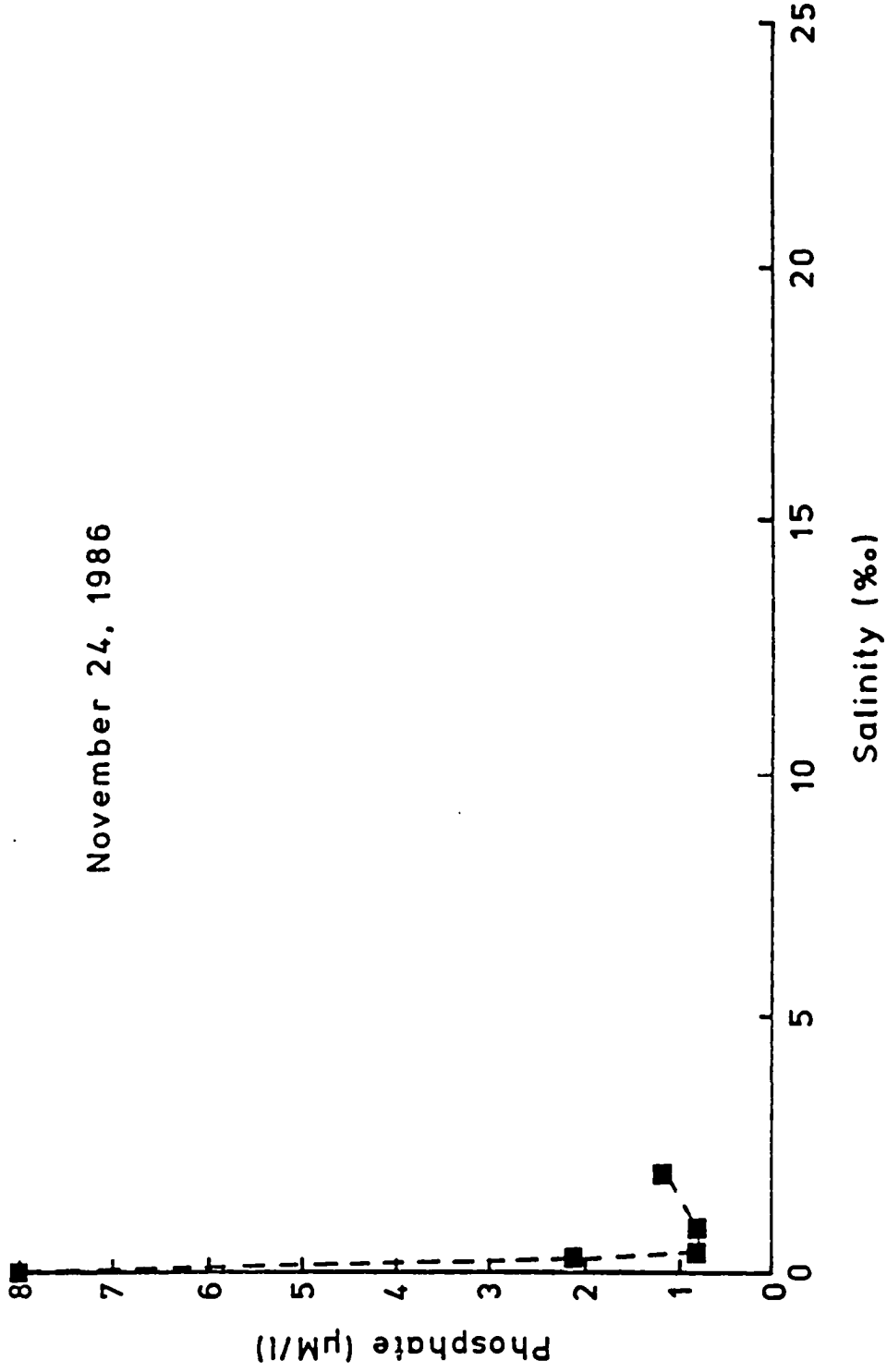


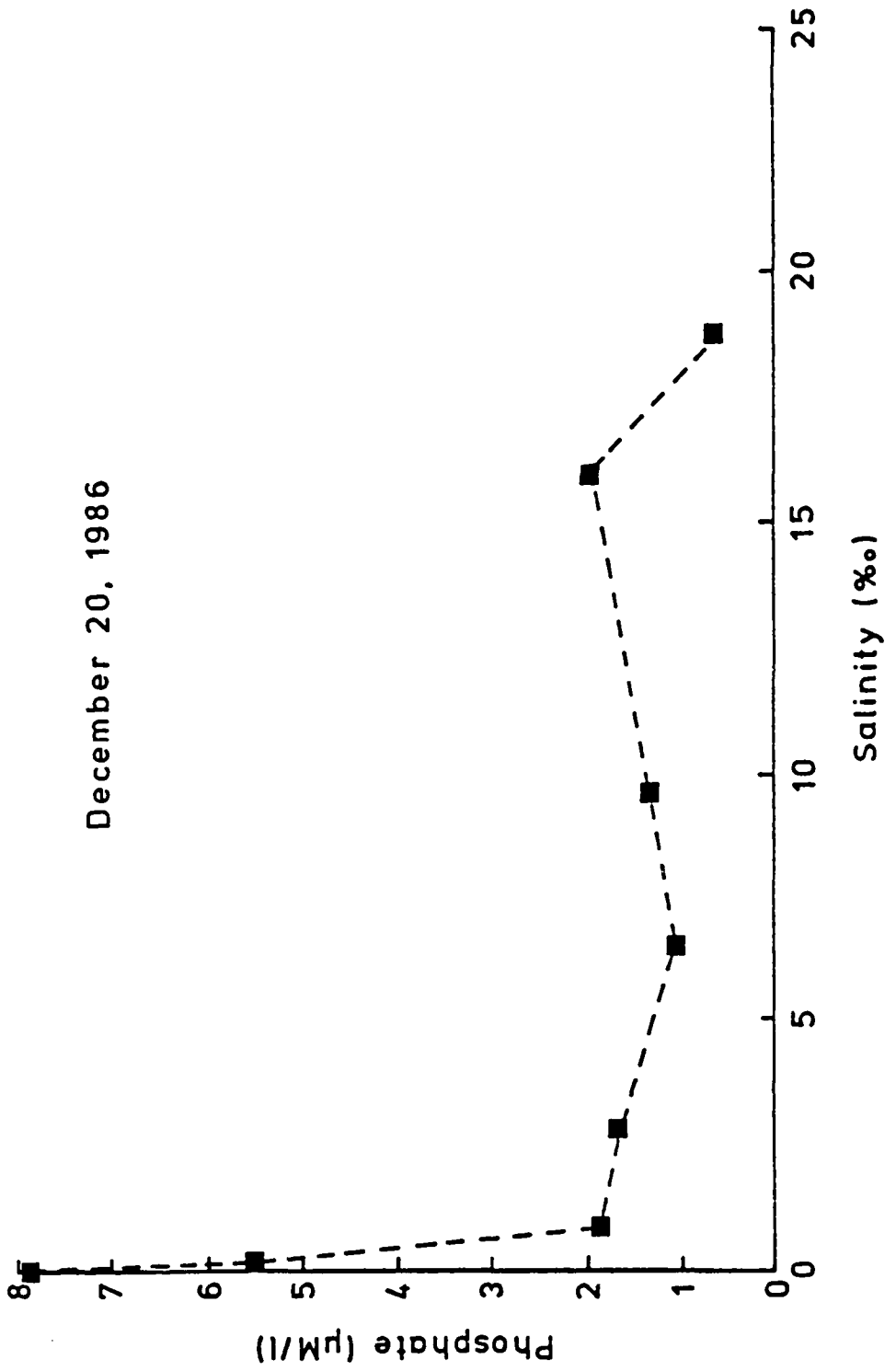


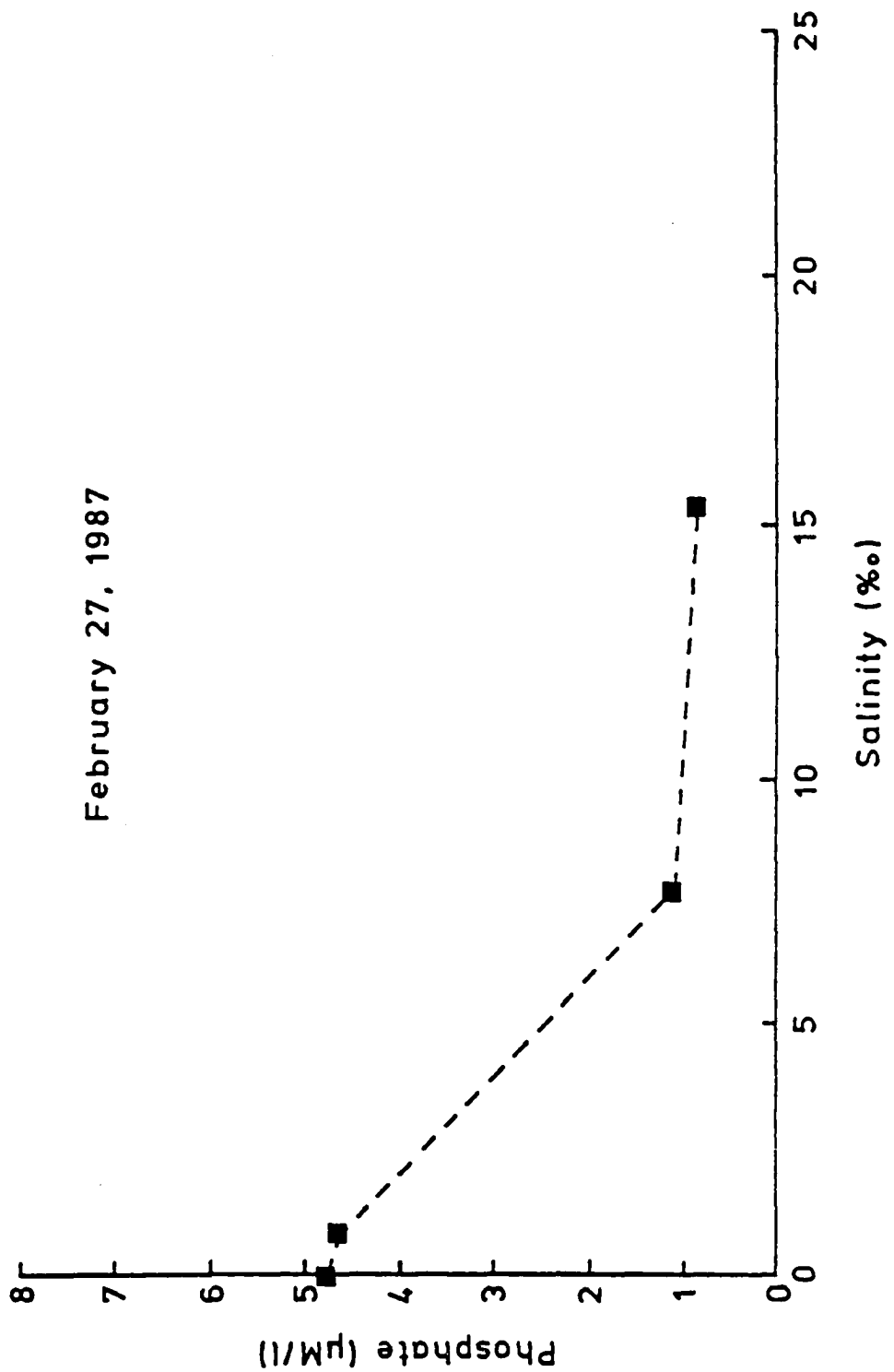


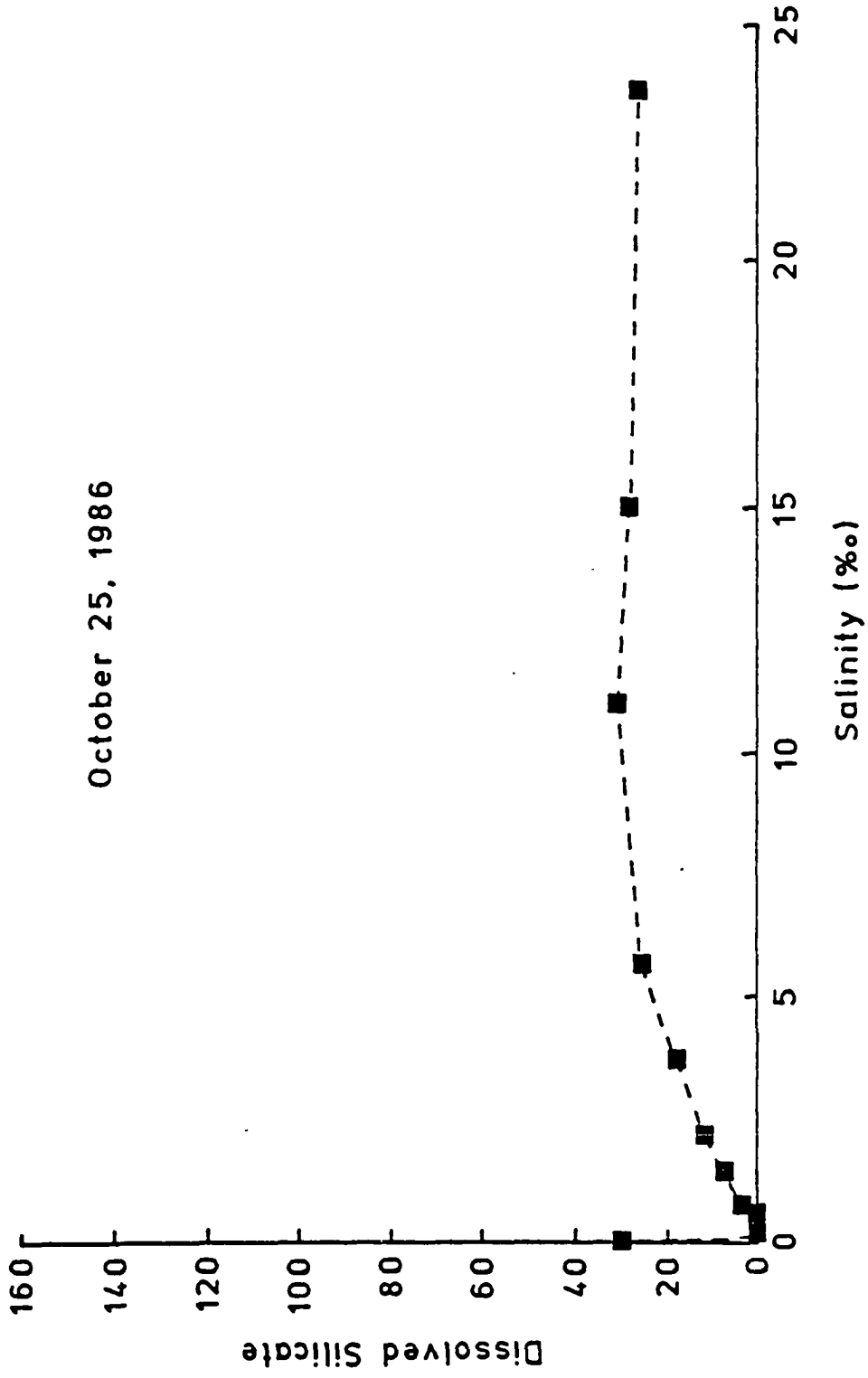


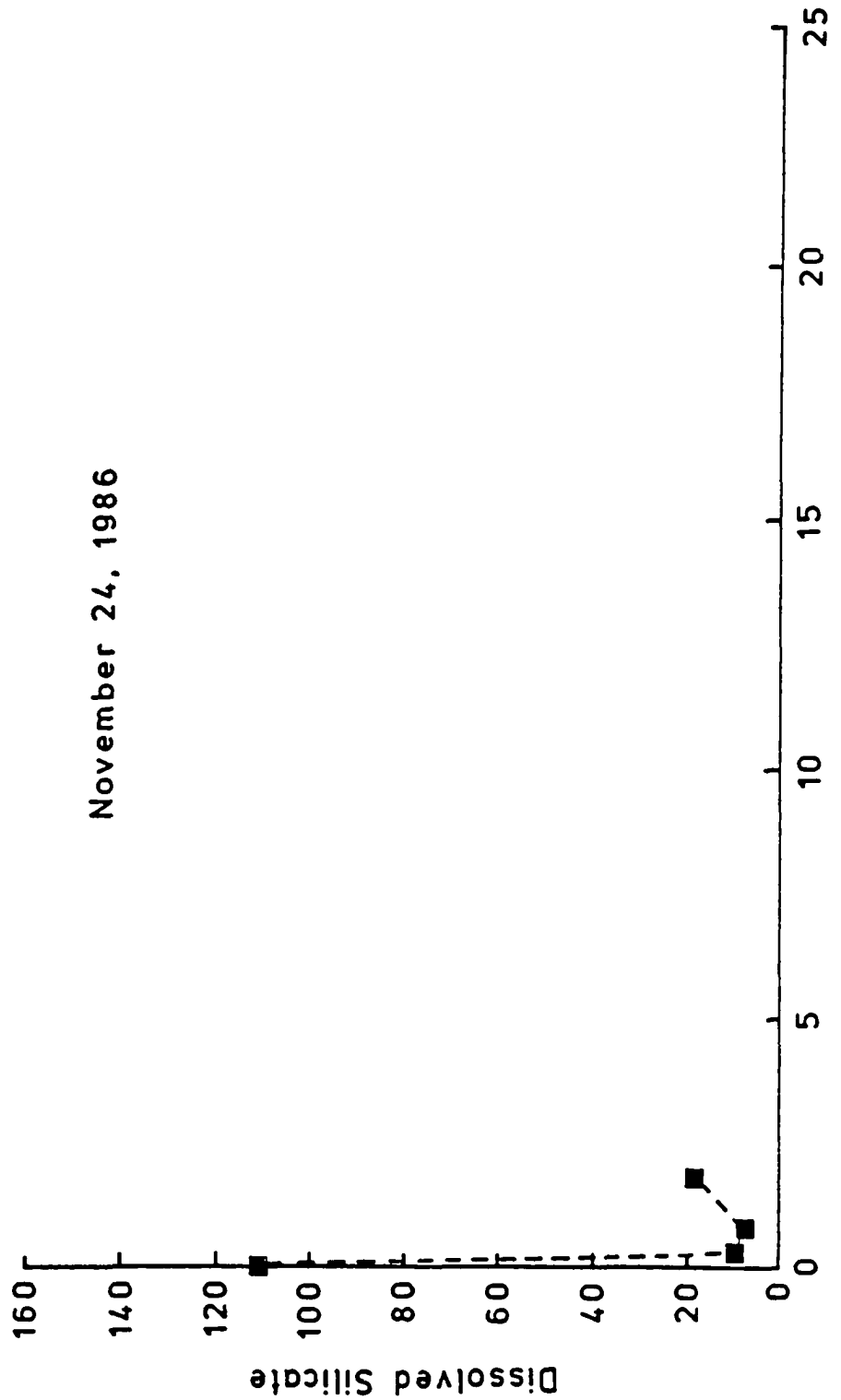


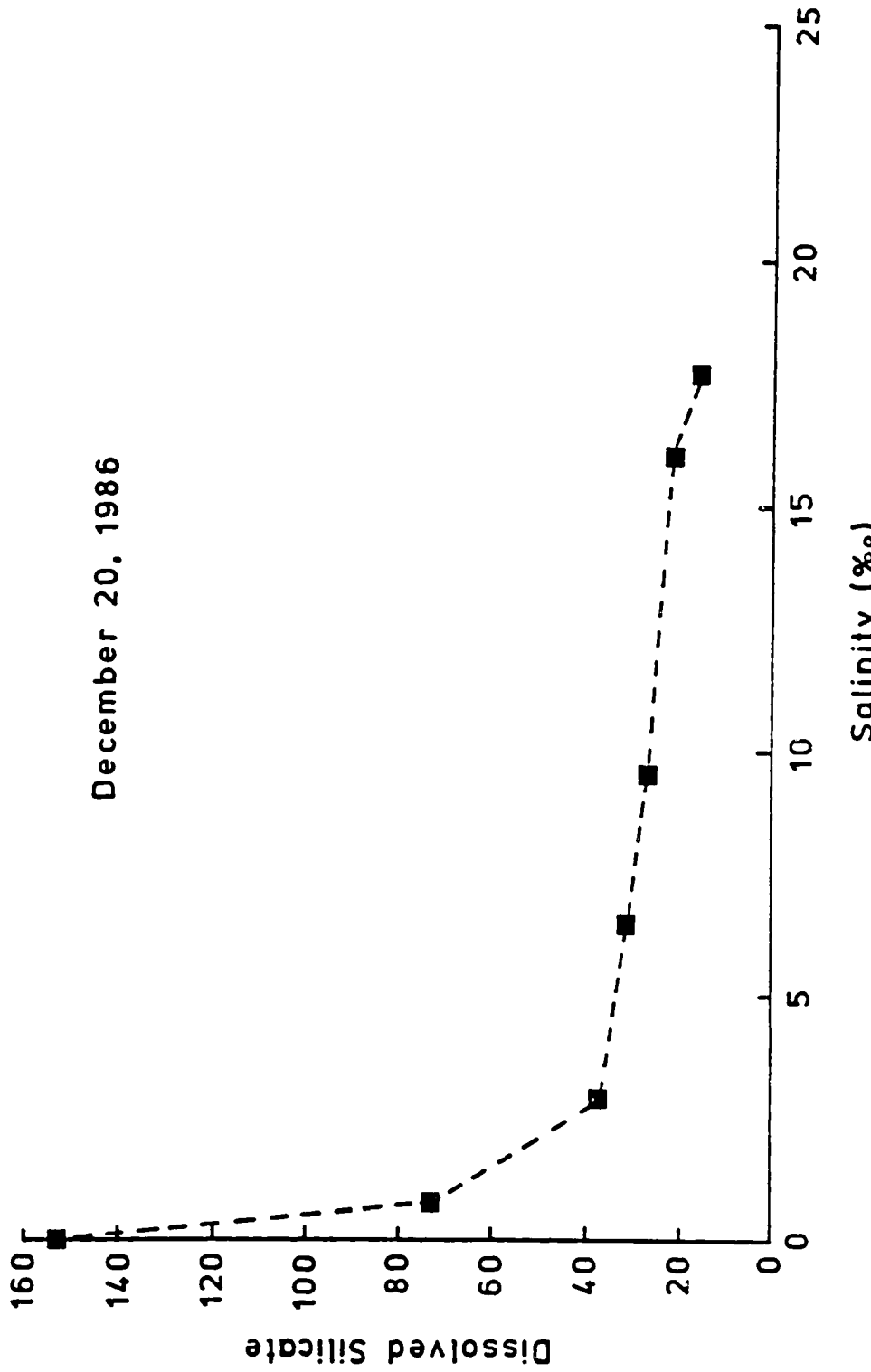


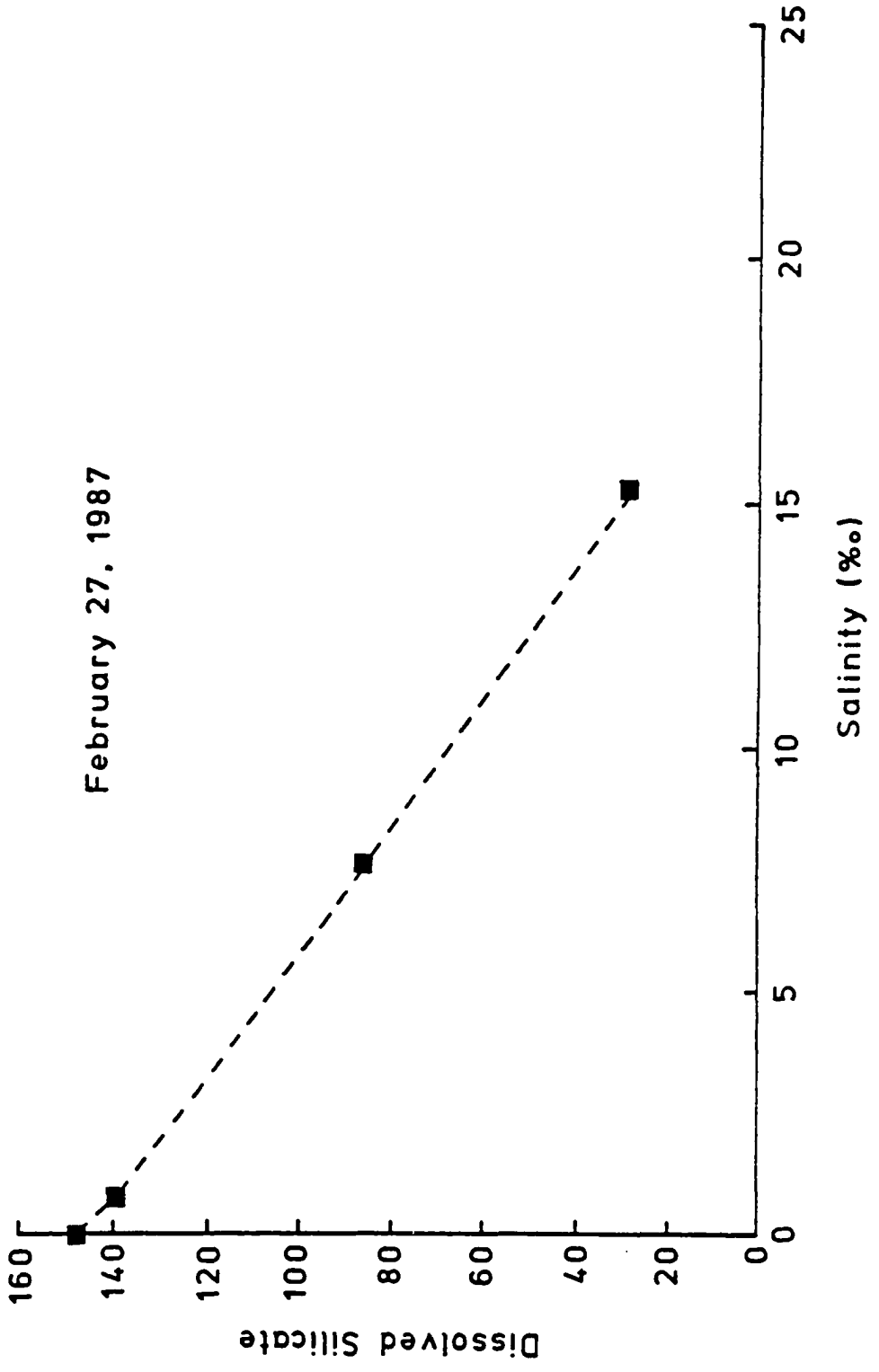












APPENDIX I. SINKING RATES OF DIATOMS.

Appendix I. Sinking rates of a diatom, Melosira sp, by using a Komar's equation for cylindrical-shape particles (Komar, 1980).

$$w = 0.0790 \cdot \frac{1}{u} \cdot (Ps - P) \cdot g \cdot L^2 \cdot \left(\frac{L}{D} \right)^{-1.664}$$

where w = settling velocity (cm/sec),
u = coefficient of dynamic viscosity (g/cm·sec),
Ps = density of particles (g/cm^3),
P = density of fluid (g/cm^3),
g = gravity of earth (cm/sec^2),
L = chain length (cm),
D = diameter (cm).

assumptions

parameter	5°C	25°C	Reference
u	0.0154	0.0090	Knauss (1978)
Ps	1.040	1.040	Eppley et al. (1967)
P	1.00403	1.00087	Riley and Chester (1971)
g	980	980	
L	0.02	0.02	
D	0.0015	0.0015	

AUTOBIOGRAPHICAL STATEMENT

CHANGHO MOON

BORN:

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EDUCATION:

B.S., Oceanography, February, 1979
Seoul National University, Seoul, Korea

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Moon, C. and W.M. Dunstan, 1988. Hydrodynamic Trapping as a Mechanism for the Phytoplankton Biomass Peak in Low Salinity Estuarine Water. Estuarine, Coastal and Shelf Science. (in preparation)

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